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ACN Handheld System Design Study Team Report

Prepared for:
Defense Advanced Research Projects Agency
Sensor Technology Office
(Initially Information Systems Office)

By:
Massachusetts Institute of Technology
Lincoln Laboratory

Prepared with Contributions from:
Air Force Rome Laboratory
Air Force Wright Laboratory
Army CECOM
Joint Spectrum Center
MIT Lincoln Laboratory
NRaD
Naval Research Laboratory

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This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

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I. Executive Summary

After the DARPA UAV Communication Node Study of 1995 was completed, three follow-on studies addressing particularly challenging areas were initiated by DARPA ISO. This report covers one of the three and addresses the challenge of providing new communication services to users with handheld radios via an Airborne Communication Node (ACN). The two other studies addressed EMI and Antenna Issues and Communication Controller and System Interconnections.

Concomitant with the ACN studies, the DARPA/ISO Warfighter's Internet (WI) study was also taking place. Because of the close relationship between these programs, advantage could be taken of results from each by the other. Indeed, in the fall of 1997 DARPA made the relationship between ACN and WI more explicit in order to ensure that the technologies and design would be integrated. Therefore, the reader will see strong similarities between the conclusions expressed in this report and those of the Warfighter's Internet study.

The goals of this study were to:

1. Define a realistic set of services that could and should be provided by a high altitude long endurance Airborne Communication Node (specifically the Global Hawk) to users with handheld radio sets. (Because there is no set of "Requirements" per se reliance was placed on previous studies that described relevant scenarios as discussed below.).
2. Provide a basis for the specification of ACN handheld services (this was delivered in June 1997 in anticipation of a contract solicitation).
3. Investigate the applicable means to provide these handheld services, including the potential use of COTS and/or GOTS technologies. This is a major theme that runs through the entire report.
4. Recommend a system architecture and design approach.

An outline of the report and a summary of principal conclusions is given below.

Section II (Introduction) gives the motivation, goals and context for the system. Scenarios are described in which a high altitude unmanned airborne platform such as the Global Hawk equipped as a Airborne Communication Node (ACN) can provide useful services to highly mobile forces with handheld communication devices. These forces require connectivity among themselves and also to repositories of data that may reside in theater or even in CONUS. This introduces the concept of asymmetric services which is felt to be an important characteristic.

Section III (Desired Services) describes the desired services to be provided to the handheld user. These services are divided into four types, however it is emphasized that they really should be implemented as a single integrated data transport architecture. The four service categories are:

1. Circuit-oriented ("PCS-like") Services for voice and other streaming data.

2. Data-oriented ("Internet-like") Services that provide the typical interactive computer-computer services that are becoming more prevalent at all force levels
3. Tactical Broadcast Service (a few Mbps) which can be composed of a subset of the Global Broadcast Service (GBS) stream plus data injected in-theater.
4. Paging Service for low data rate messaging and alerts

Section IV (System Architecture) discusses several architectural alternatives, and recommends a "base station-centric" approach which includes on-board ACN signal processing. It is also recommended that the architecture be asymmetric, i.e., that downlink data rate should be able to exceed that of the uplink to and from individual users. Recommendations for uplink and downlink signal structures and access techniques are given. Comparisons are made to COTS systems.

Section V (Link Performance Factors) describes a number of technical factors that will enter into the design of the physical layer aspects of the system including propagation and jamming. The difficulty of predicting exact performance measures will be seen, thus emphasizing the need for adaptive signaling techniques.

Section VI (Frequency Selection Factors) summarizes key technical issues in the selection of operating frequency. However, frequency allocation constraints are at least as important. A separate report prepared by the Joint Spectrum Center (JSC) addresses this. One conclusion is that the ACN handheld system will need to be frequency agile for worldwide utility.

Section VII (Implementation) presents aspects of system implementation from a hardware point of view. Two particular aspects are discussed in some detail: antennas and uplink signal processing.

Sections VIII and IX (Applicability of COTS and GOTS Technologies) discusses a number of COTS and GOTS technologies that are potentially relevant and gives their shortfalls and applicability. A major conclusion is that there is no COTS or GOTS system that provides a complete "plug and play" system solution. However, there are specific technologies and components that are applicable and should be pursued.

Section X (Summary of Conclusions and Recommendations) presents a summary of conclusions and recommendations. Principal among them are:

- A multi-Mbps multimedia handheld communication service using the ACN is feasible
- ACN handheld services should be tightly integrated with mobile networking concepts such as those explored in the Warfighter's Internet study
- An asymmetric architecture (lower rate uplink than downlink) is recommended
- Adaptive, flexible physical links integrated with upper level protocols and applications are desirable
- There are numerous GOTS and COTS (or in development) subsystem, component and protocol technologies that are applicable

- No COTS or GOTS system has been identified as a complete "plug and play" solution to providing secure, flexible, efficient and scalable ACN interactive handheld services
  - COTS does not meet minimal AJ and LPD requirements
  - Cellular, PCS and MSS systems are limited by their symmetric circuit-switched architecture (although data services are evolving)
  - Wireless LANs do not provide asymmetric services with low rate uplinks
  - The commercial market should continue to be tracked
- Useful near-term demonstrations of the ACN/HH concepts can be achieved with off-the-shelf components, but will not have the capacity, efficiency, range, security and form-factor of a final system
- A flexible approach to the selection of operating frequency and bandwidth is necessary
- Development is required in the areas of
  - detailed system design
  - integration with Warfighter's Internet networking concepts
  - detailed physical layer designs and protocols
  - efficient uplink multi-channel multiple access techniques
  - realization of on-board processor
  - adaptive robust physical links
  - ACN antenna concepts: shaping, sectoring, nulling
  - low power handset components
  - interfacing with legacy radio networks
- Useful near-term demonstrations of the ACN Handheld (ACN/HH) system concepts could be accomplished using off-the-shelf components, but will not have the capacity, efficiency, range, security and form-factor of a final system

A separate report (prepared by the Joint Spectrum Center) addresses frequency allocation issues[JSC].

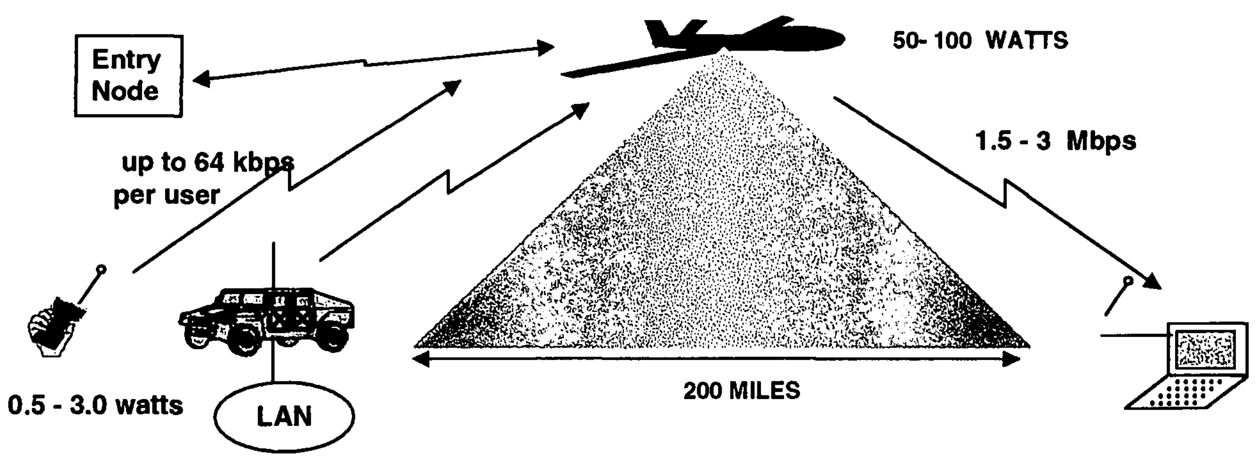
II. Introduction

This introduction provides the motivation for performing this study and the goals that it hoped to achieve. The rest of the report is devoted to exploring the technical issues and presenting the conclusions.

A. Motivation

Airborne platforms such as the Global Hawk provides a highly desirable platform for use as an Airborne Communication Node thanks to its ability to be launched and retrieved far from its theater of operation, its high operating altitude, and long loiter time. It is particularly valuable for early entry and clandestine operations when a significant communication infrastructure may not be available or prudent to use

Previous studies, e.g., Extended Littoral Battlespace and Sea Dragon, have shown that in these situations an ACN can provide important communication services to personnel with "handheld" communication equipment, i.e., equipment with the size and weight of cellular phones and having minimal orientation and positional restrictions. This would provide true communication-on-the move capability. As illustrated in Figure II-1 the communication equipment, in addition to providing voice service, can be connected to portable computers or capable personal digital assistants for enhanced digital communication services and applications. It is highly desirable that these services, e.g., voice and data, be provided with apparent simultaneity to the user.



- "PCS-like" voice
- "Internet-like" data
- Tactical Broadcast Service
- Paging

Figure II-1 Handheld Services

It should also be noted that an airborne relay or network of relays is not planned to be the only means of providing battlefield communication to mobile users. There will be a continuing need for direct peer-peer communication, e.g., SINCGARS and other radios, tactical SATCOM, and almost certainly a growing use of commercial personal satellite communication. It is not the intent of this study to trade-off all of these modes against an airborne relay, but rather to develop an approach for the most effective airborne relay system in itself which can then be rated in comparison.

While the importance of handheld communication is clear, the most effective means to implementing it has not been. A common suggestion that arises is the use of COTS cellular, or PCS technology, i.e., "why not fly a commercial base station?". While appealing at first look, this direct approach will be seen to have serious shortcomings in the context which will be described later in this report. There are potential other COTS or GOTS technologies that will also be examined. The COTS and GOTS issue should not be thought of completely "either-or". Indeed, there are service models, protocols, chipsets and other techniques that are extant in the civilian and government worlds that can be directly applied to the handheld communication solution. Thus it is recognized that although commercial systems may not meet all military needs, significant technology within these systems may be adapted to create a cost-effective solution that does.

B. Scenarios

It is helpful to describe some scenarios in which handheld communication via an ACN would provide a major pay-off. In particular, contingency and early entry assaults as described below and in [WI] are representative examples.

Contingency operations as depicted in Figure II-2 are likely to be comprised of small units, rapidly deployed, and at long range from their support services. Tactics involving small unit operations (SUO) may be used where teams of 10 to 20 soldiers are deeply deployed to determine enemy movements and then call in massive indirect fire rather than engaging the enemy directly. Special Operations Forces (SOF) operate in a similar manner, although traditionally they have only their own resources for support, and rely on stealth and surprise for success. The SUO depends on long-range communications (BLOS) for success. However, heavy communications infrastructure is inconsistent with their light armament and deployment methods. The use of simple line-of-sight radios to reach an airborne communication node which in turn is able to relay messages from user to user as well as from Theater and/or CONUS command and support services is an effective way to provide the connectivity these forces need. Through this node can flow needed command and control traffic, ISR products, and requests for medical, logistic, and fire support services. The majority of this traffic is (bursty) computer data, but it also includes (continuous rate) voice and video.

Amphibious assault is another scenario that can benefit from an airborne communications network, and is typical of early entry situations with limited support infrastructure. Future amphibious assaults will likely be carried out with fleet resources over the horizon from the beachhead or landing zone in order to protect ships from cruise missiles. Troops arriving from

landing craft and from helicopters will not have the ability to bring with them heavy communications infrastructure.

Even in more conventional force deployments, there will be situations where some forces have lost line-of-sight connectivity with the rest of the forces, due either to rapid maneuvers or to geographical factors (such as intervening mountains). The airborne network can provide the needed connectivity in this case as well.

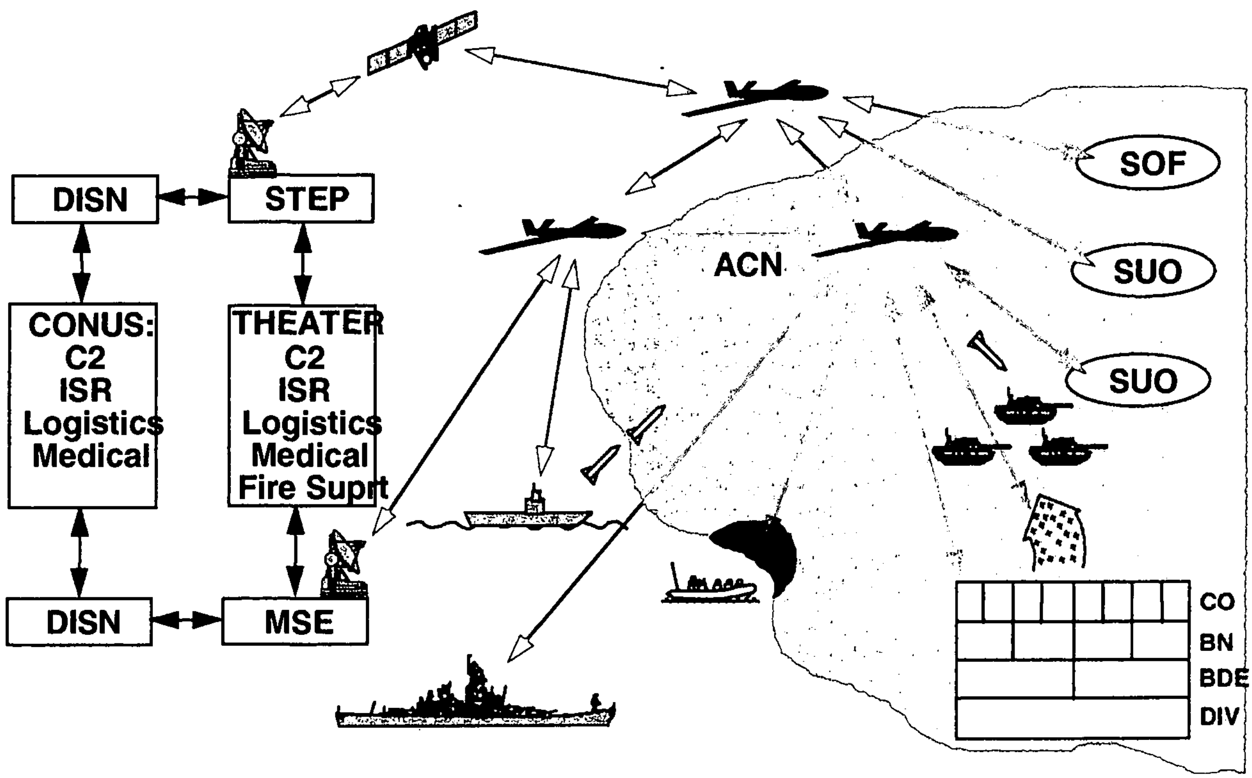


Figure II-2 Representative Scenario

C. Interconnectivity

Figure II-3 shows the interconnectivity that is implied for the ACN handheld unit. Primarily, of course the handheld unit will connect with the ACN. In turn, the ACN will be able to interconnect an ACN handheld user with:

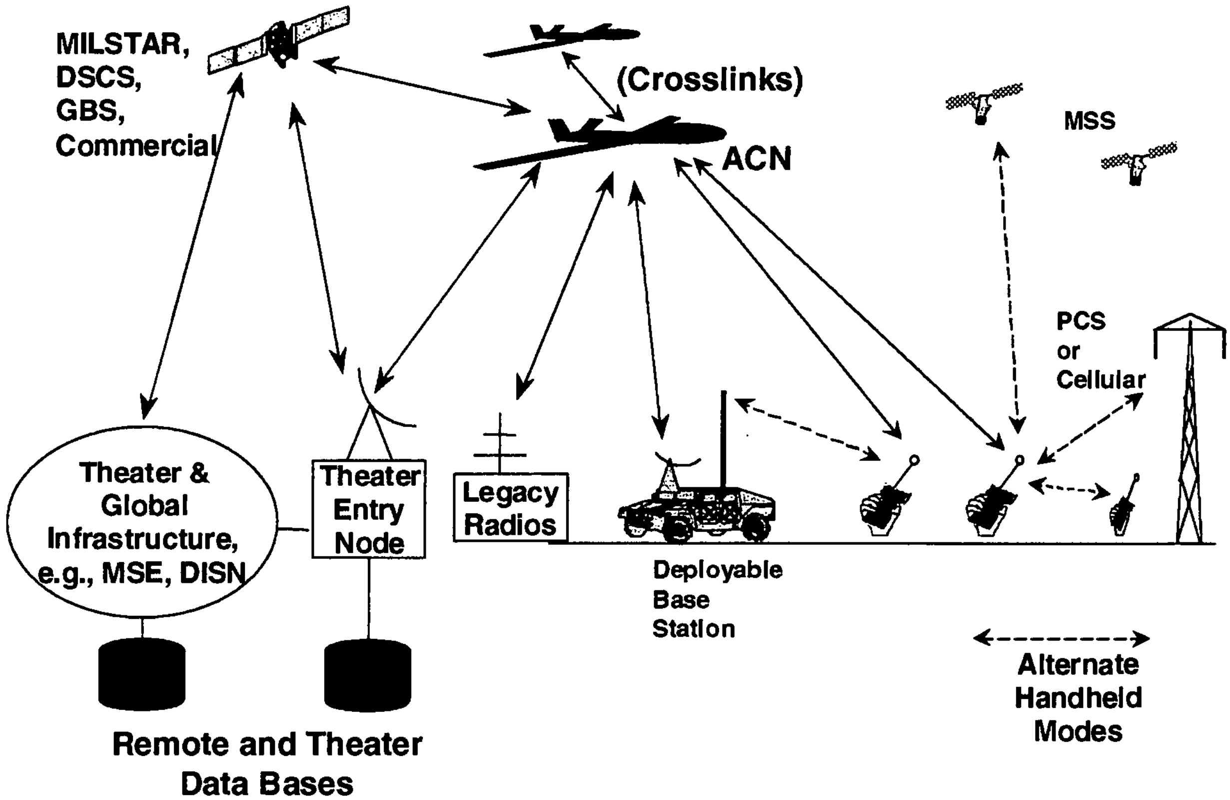


Figure II-3 Connectivity

- other ACN handheld units connected to the same airborne platform. These units may be connected point-to-point; or as fully connected nets similar to combat net radio; or as a packet data network with multicast features.
- other ACN handheld units that are interconnected to other airborne platforms via crosslinks.
- legacy radios, e.g., SINCGARS, and HAVEQUICK
- theater and global communication infrastructure, e.g., MSE and DISN, as circuit or packet data internetworks.

The connection to the theater and global infrastructure is important to emphasize, for it is believed that the handheld users will rely on this for timely access to large amounts of data that can either be "pulled" or "pushed" from theater or remote servers. For example, it is expected that the Global Broadcast System satellite downlink (operating at a rate of over 23 Mbps) will be received at a theater entry node, filtered then mixed with theater-generated traffic and rebroadcast (at a lower rate) to handheld users. Other examples include user access to theater data bases, e.g., weather, situational awareness, and email.

(Also shown are a number of alternate modes that may be desirable for the handset to support. These include: terrestrial commercial infrastructure if available; commercial mobile satellite subscriber (MSS) satellite services; connectivity with DoD deployed cellular-like base stations; and a direct peer-peer mode as is under development by the Small Unit Operations (SUO) program. The inclusion of these modes in a handset raises design issues similar to those

faced by multi-mode cellular handset manufacturers. While inclusion of these alternate modes in the handheld radio may be desirable, they do not have to be supported directly by the ACN itself and therefore are not considered further in the discussion to follow.)

III. Desired Services

There are four basic services that the ACN should provide and these are described below. However, these services should in fact be considered as four facets of a single integrated ACN data service for handheld users.

To go further, it is recommended that all of these services be available to the user with apparent simultaneity. The architecture that is recommended will accomplish this.

A. Circuit-Oriented ("PCS-Like") Services

Circuit-oriented or "PCS-like" services refer to the services that are normally associated with cellular telephone, the newer PCS systems, and the emerging MSS (mobile satellite systems). The term "PCS-like" is being used to characterize the type of service, and not to imply that an existing PCS or cellular realization will satisfy the needs of the DoD on ACN.

PCS-like systems generally provide circuit-switched point-to-point rate-symmetric connections which can be used (with appropriate external devices) for such services as voice, FAX, low rate video, and PPP dial-in data connections. (Commercial PCS systems also include a paging service.) For DoD usage it would also be desirable to include a net broadcast mode (one transmit, several receive) which is similar to combat netted radio, but which is not generally available in commercial systems. Although the physical connection is much like that of a telephone's dedicated circuit, the data itself (even if voice) may be formatted as packets for maximum flexibility in interconnection and routing with other systems. (Some commercial systems support a direct but limited data capability, but voice is carried as a separate stream and is not simultaneous with data.)

Previous studies [DARPA ACN] have suggested that about 200 voice circuits should be provided by the ACN.

The individual voice circuits can be supported at high quality with data rates as low as 2400-4800 bps as is now planned for some commercial systems, e.g., Iridium.

B. Data-Oriented ("Internet-like") Services

It is anticipated that in the future there will be a significant DoD need for data communication services to support a wide variety of applications that are based on the "Internet paradigm", e.g., client-server and connectionless message transactions (such as e-mail). Many of these transactions are asymmetric, involving short bursts of uplink user activity followed by either lengthy downlink data transfers from servers or short acknowledgments. The "PCS-like" circuit-oriented services described above will not make efficient use of power or bandwidth to efficiently support these low duty-cycle bursty activities.

It is suggested that an uplink capacity be provided of about 0.5 Mbps to be shared among several hundred or perhaps thousands of handheld users . A rate of a few Mbps would be the corresponding downlink data rate, reflecting the asymmetric nature of this service.

C. Tactical Broadcast Service

A Tactical Broadcast Service for forces on the move is an attractive ACN feature. It is desired that this service operate at a rate of about 1.5 Mbps (T-1). This broadcast could include a subset of the 23 Mbps streams carried by the GBS (Global Broadcast Service). It could also include information such as Situation Awareness data that is generated in-theater. The information to be broadcast may come from a single injection site or conceivably from a distributed collection of sources and multiplexed on-board the ACN. An addressing mechanism will be employed so that individual receptors or multicast groups would have the means to filter the broadcast stream in order to determine which data to process. Individual receptors should also have the capability to request or "pull" desired data into the TBS using the Internet-like reverse link from the end-user to the TBS originator(s).

D. Paging Service

A paging service can be used in a variety of ways. Individuals (or multicast groups) can be paged in order to elicit a communication response or to convey short messages. This service can also be used for rapid dissemination of battlefield warnings, e.g., CBW attack. While pages may originate from a terrestrial paging center is should also be possible for individual user to generate a page for other users. It should also be possible for users to acknowledge pages which are directed to them. The paging system should be able to operate at relatively low rate with the ability to deliver several hundred messages per hour of nominal length 1000 bits.

E. Integration of Services

Each of the services above has been described as though it were a separate entity. However, there are major advantages to integrating these services and treating them as different ways to use an available pool of resources. Reasons for doing so may include: 1.) It would permit a smooth reconfiguration of resources to respond the operational needs, e.g., more voice and less data. 2.) It would reduce the number of separate developments or procurements. 3.) It would permit the same equipment to perform more than one function simultaneously, e.g., a handset that can receive a broadcast and also serve as a voice terminal or transmit voice and data with apparently simultaneity. 4.) It could reduce EMI and antenna coupling design problems on the ACN by reducing the number of transmitters and antennas.

In addition, Internet capabilities for handling streaming traffic (voice, video, other real-time data) more easily than today are being developed and standardized through the Internet Engineering Task Force (IETF). Thus Internet-like services of the future are expected be broadened to include these services as well, thus naturally evolving towards further integration of services.

These reasons in favor of integration must be weighed against those opposed, including the possible increase in difficulty of obtaining frequency allocations to support an integrated service.

F. Support Services

There are additional supporting services illustrated in Figure III-1 that should be provided as discussed below. As shown in the figure some of these services are an integral part of the handheld system itself while some might be considered as "network" services and would be provided by units located remotely to the ACN itself. Also shown is a crosslinking system that could be used to interconnect airborne platforms into a theater- area backbone.

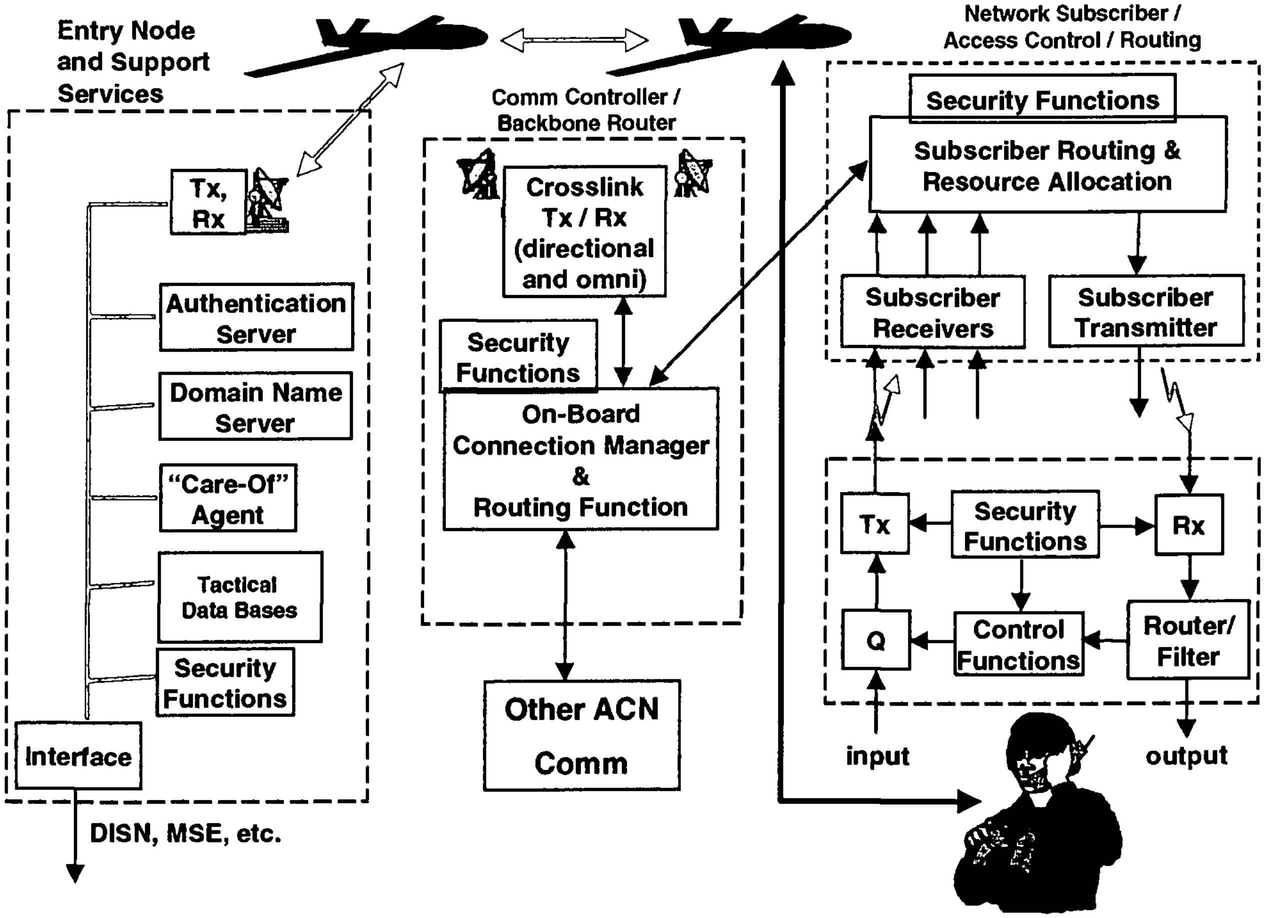


Figure III-1 Functional View and Supporting Services

1. Mobility

The ACN must support mobile users and is, of course, mobile itself. "Mobility" here refers mainly to the fact that it will not always be possible to pre-plan which terrestrial users will be assigned to which ACN. The system must therefore be able to perform the functions of user registration and tracking (including handover from airborne platform to platform as well as beam to beam), as does a commercial cellular system. In addition, user location information must be made available to networking routers so that packet data can reach the intended user rapidly.

2. Security

It should be assumed that the ACN must employ means of offensive and defensive information warfare. Although it is expected that all end-end user communication will be encrypted with an appropriately approved device, this generally will be outside the responsibility of the ACN communication system except for interfacing and control. Within the system, protection must be provided for:

- user authentication and access control
- cover of user traffic characteristics
- cover of user signaling
- cover of user location
- cover of ACN location
- spread spectrum sequences

IV. System Architecture

Wireless systems have some severe disadvantages in comparison to wired systems, and with the widespread introduction of high data rate fiber cables the relative transmission rate disadvantages are increasing. However, the desires of the users in terms of applications is being conditioned by what they see on workstations on a wired network while in garrison, that is, in communications-rich and computationally-rich environments. The challenge of the ACN Handheld (ACN/HH) system design is to approximate the utility of some of these applications in deployments with communications-poor and computationally-poor environments.

This section discusses key architectural issues that address this challenge. These issues center on providing the desired capacity and services while being efficient in the use of resources, i.e., power, bandwidth and weight. It will be seen that the architecture being recommended includes a "base station-centric" approach with on-board ACN processing as opposed to the use of transponders. The latter will be discussed at the end of the section.

A. Communication Architecture

There are a number of reasons why mobile communications systems are typically organized in a cellular fashion with base stations tied together with a backbone. First is the propagation environment with sources of blockage and attenuation. Second, in cellular systems accommodating large numbers of users, frequency allocation is a major limiting factor, and elaborate schemes have been designed to allow reuse of bandwidth so that the aggregate capacity is reasonable.

When a cellular communication organization is applied to military situations, there are further constraints on bandwidth. Jamming reduces communications margins and one may have to tradeoff available bandwidth (capacity) for jamming protection. Moreover, there is some flexibility in commercial cellular systems: one can subdivide cells and reuse the bandwidth further. This strategy is not practical with airborne platforms: more aircraft may be not be readily available and those that are may be forced to service large footprints.

The fundamental fact is that it will be necessary to live with limited capacity. But the available capacity can be used to maximize the throughput seen by users by applying two design rules:

1. Utilize the available communication capacity in the most efficient manner possible
2. Develop applications that require the minimum amount of communications resources

It has been suggested that the ACN/HH should provide service for applications based on the Internet paradigm and should organize the connectivity of subscribers (Warfighters) in a manner similar to cellular telephony networks. Internet and cellular-oriented telephony networks are vastly different technologies but the ACN/HH must be built as a blend of the best features of both. In particular, the subscriber terminal should be "small" and highly mobile as in cellular telephone systems, while adapting the statistically-multiplexed, connectionless data transfer nature of the Internet for bursty traffic to provide efficient use of the limited wireless bandwidth.

Potentially the ACN/HH must support a very large number of subscribers covered by a few airborne nodes. There is no predicting the geographical distribution of users and it is feasible that many hundreds of users can be covered by the same airborne node. While the majority of users will not be active at the same time, one can be sure that on many occasions many tens of users will want to participate in active communication sessions. One can build into the airborne node the equivalent of a cellular base station where each end point in the base station effectively has more communications capability than the Warfighter terminal. This asymmetry in capability (and complexity) means that the ACN/HH terminal can be made smaller and less complex by allowing the base station to provide more of the complex processing. Additionally, the base station provides mechanisms for controlled channel access by the Warfighters desiring communications.

With a point-to-point radio architecture, one would need as many dedicated channels on the airborne node as there are active sessions. One would further need a means of matching a subscriber to an available asset on the airborne node; this would require a design modification to the way that point-to-point radios typically operate. Even assuming that this modification is executed, it is still clear that the dedicated asset will normally be severely underutilized for bursty data services. This last point is hard to mitigate without a radically different communications architecture.

A base-station-centric design can provide additional flexibility in terms of channel utilization. A common way to organize any hub centered (star) network is to assign circuits for the length of a communications session. However, when bursty data is the information to be transferred, this dedicated resource may run at a utilization efficiency of less than 1%. For voice the efficiency may be as much as 40% (which is good). However, if data is to be the bulk of the traffic (actually the equivalent in session connect time), then circuit-oriented assignments are a very inefficient choice. This is why statistical multiplexing schemes have been developed. Connectionless systems are a very efficient in statistical multiplexing of bursty traffic and the Internet is the prime example. Today the Internet does not handle streaming traffic (such as voice) well; IPv4 does not have built-in provisions for QoS specification that would serve streaming traffic appropriately. On the other hand, the evolution of IP to IPv6 will provide QoS specifications for several types of traffic, including voice. But whatever protocols are used they must provide for both bursty and continuous traffic, and they must provide the service on demand (no dedicated circuits waiting to be filled).

Lastly we note that it should be expected that data flow to and from each user (and hence on the downlink and uplink) is expected to be asymmetric. Handheld users will not only be communicating with each other (a roughly symmetric data flow) but will be drawing data from various servers that may reside in the theater, at theater-rear or even in CONUS as illustrated in Figure II-3. This asymmetry is seen regularly when examining actual data flows in and out of most organizations that are connected to the Internet. In/out ratios (corresponding to downlink/uplink) of 4 to 10 are not uncommon.

B. Recommended Asymmetric Architecture

It is useful to examine the downlink and uplinks separately when considering the communication architecture. It should first be noted that there are two main factors causing an asymmetry between the uplink and downlink that should be taken into account:

1) the transmitted power from an uplink user will be at least an order of magnitude less than that which can be used the ACN's downlink transmitter (about 1 watt compared to 50 watts); hence the data rate from the ACN can be correspondingly larger. As will be discussed in Section IV (Performance), the uplink data rate from any one terminal will be in the range of several 10's of kbps, while the downlink rate can be a few Mbps.
2) the data stream from the ACN (consisting of the aggregate of data for all users) can be carefully assembled, scheduled and packed whereas the data uplinked from any user must contend for resources in a generally unscheduled manner.

Advantage of this significant asymmetry can and should be taken into account. This has led to the architecture illustrated in Figure IV-1 which shows the basic notion of a number of relatively low rate uplinks from a large number of users and a high rate downlink that is dynamically shared.

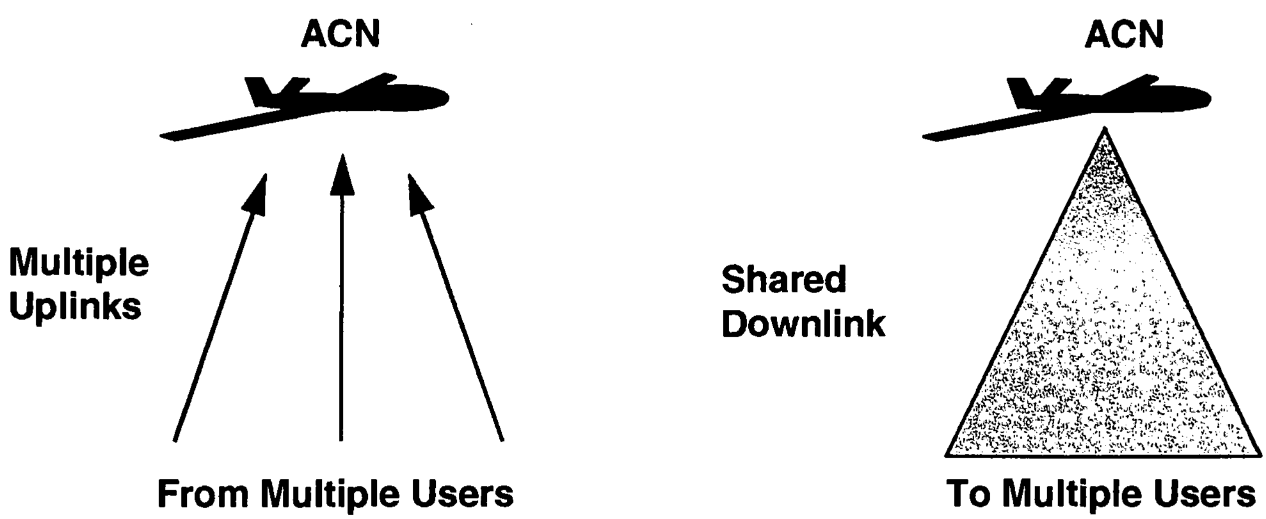


Figure IV-1 Asymmetric Uplink and Downlink Structure

Figure IV-2 shows more detail and circumscribes the portions of the ACN handheld system being addressed by the study. In particular, this study concentrated on the architecture of the physical links and access to them. In a layered architecture, this corresponds to the physical, medium access control and data link layers. The issues pertaining to higher layers, in particular the network/internetwork layer have been addressed by the Warfighter's Internet study although clearly the all of the layers must be addressed in concert.

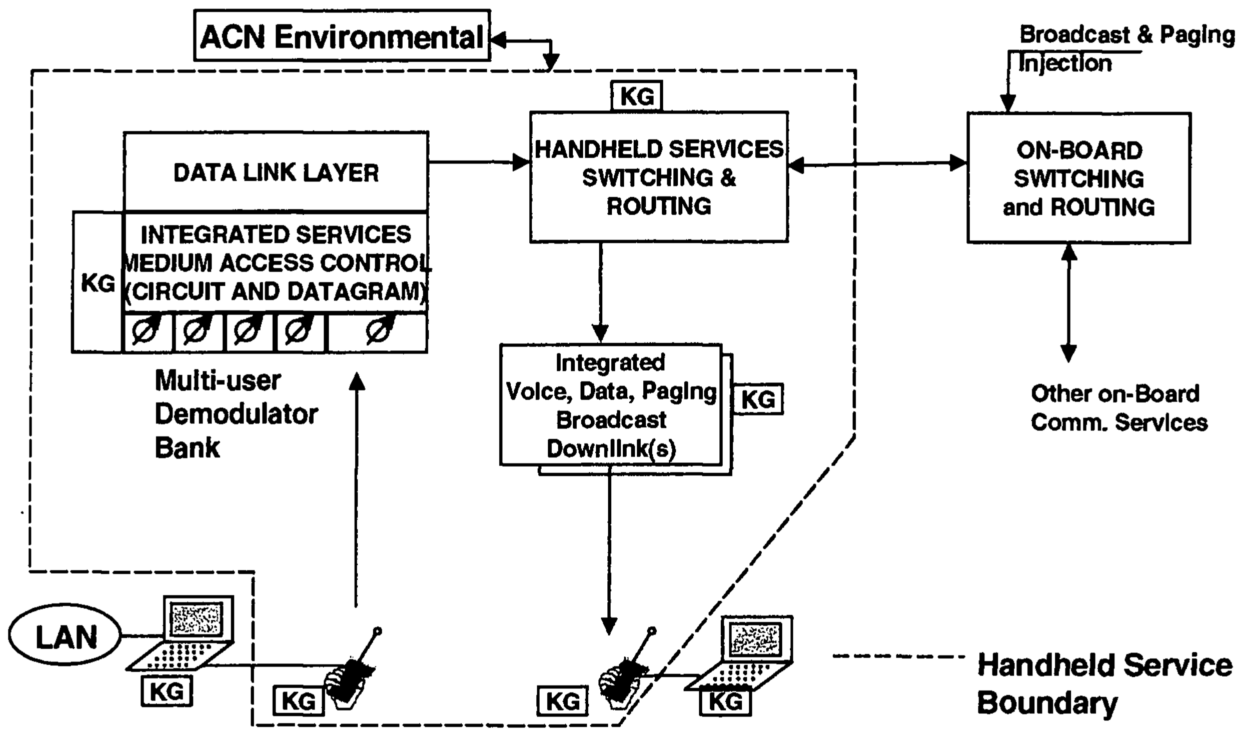


Figure IV-2 Handheld Service Elements

C. Efficiency of utilization

The communications capacity of the uplinks and downlinks between the airborne platforms and the individual subscribers are the most limited resources. Not only should these resources be assigned on the basis of need, but the signaling techniques used on these wireless links must make the most efficient use of the available data rate and frequency allocations. This design must take into account the heterogeneous nature of the communications traffic: it is expected be predominantly bursty computer data, but with significant amounts voice and other constant rate traffic, e.g. video.

1. Downlink

The downlink is the simpler case. The downlink will consist of a stream of interleaved packets directed to many different users sharing this downlink beam. Since the communications will have both different real time demands and user priorities, the ACN's downlink traffic manager can efficiently schedule and interleave individual packets transmissions to match the time demands and the priorities. A traffic manager can completely fill the downlink so that lower priority excess traffic will be delayed until the higher priority traffic is serviced. For steadily streaming traffic such as voice, packets can be scheduled for transmission on a regular basis. A model for the down link from the airborne node would be that of a (wireless) LAN, where all of the traffic for all of the users under the aircraft coverage would be broadcast sequentially in packets. Each of the users would listen to the downlink stream and pick off the packets intended for them. Because of the low utilization rate of any individual user, many users normally share this downlink LAN and receive responsive service. Since the downlink is a broadcast, a further efficiency improvement can be realized when the same message is being

transmitted to multiple users. If a multicast (or broadcast) address is used, the message need only be transmitted once and all the active users can collect the message at the same time.

The downlink can be organized as a small number of shared high rate streams or a traded for a larger number of shared lower rate streams. (In a cellular telephony style system each user is assigned its own low rate downlink stream.) From an efficiency and delay minimization point of view it is advantageous to pool the downlink traffic into a single high rate stream. This is illustrated in Figure IV-3 which shows the average message delay as a function of total channel utilization and the number of channels the downlink is divided into. (The model assumes that the total system capacity is constant even when divided into separate streams. A simple M/M/m traffic model was used for illustration with blocked traffic held in the system. Messages arrive randomly and independently of each other. The message lengths have an exponential distribution. Each channel is assumed to maintain its own queue which corresponds to user receive terminals that are tuned to just one channel.)

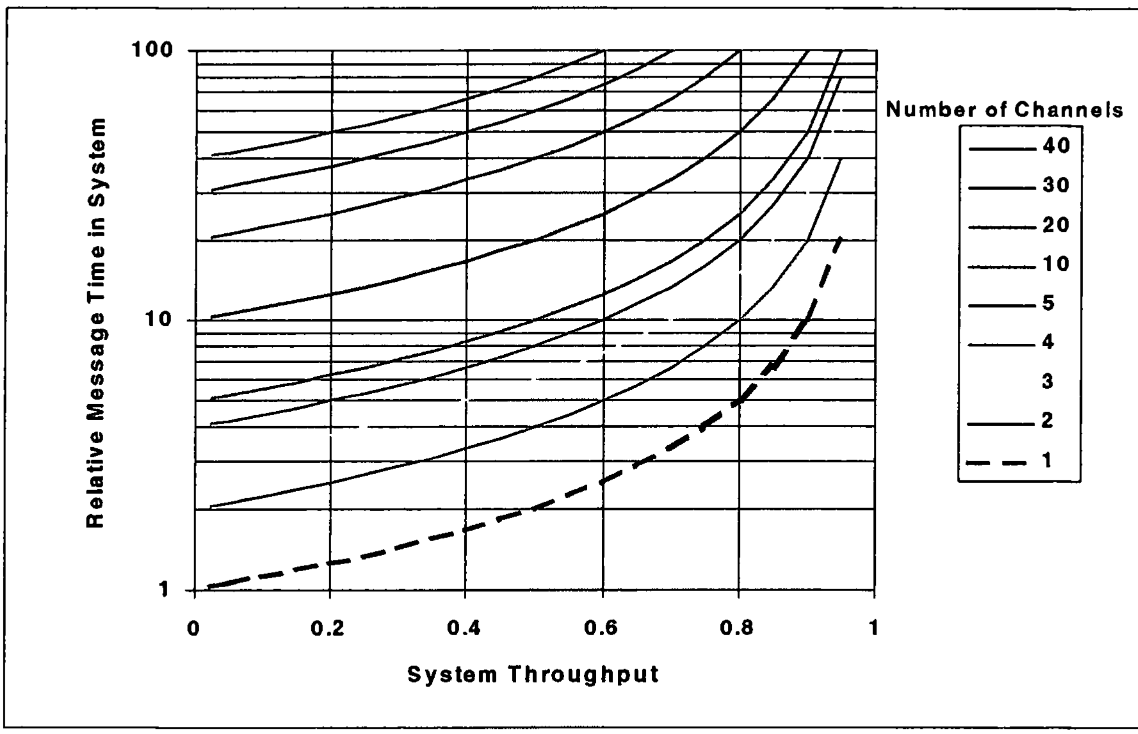


Figure IV-3 Advantage of Pooling Channel Resources

It is seen that the best performance is achieved when the data is aggregated into a single channel. This is true for two essential reasons: 1) the transmission speed is highest with one channel and 2) the queueing delays are shorter.

(Note that in systems where the bulk of the traffic is streaming point-to-point, e.g., the cellular voice systems, this argument is not as strong. However, in systems with a significant amount of rapid bursty data transactions the benefits of pooled resources is evident.)

Although the argument for a single high rate downlink stream was just made, it must be recognized that this stream will be servicing user downlinks with widely varying channel conditions. That is, some users may have link conditions that permit several Mbps to be received

while others may only be able to receive several 10's of kbps. Users should be capable of indicating their channel state to the ACN so that adaptive rate transmission can be used. Further, services such as paging should be transmitted at a low physical channel rate, in order to be robust especially since the state of the user downlink may not be known. The downlink, therefore, should actually be capable of mixing a variety of physical channel data rates in its composite stream as shown in Figure IV-4. This can be done in several ways including: time sharing of multiple rates, quadrature multiplexing (high rate on "in-phase", low rate on quadrature), separate frequencies, or various hybrids. (For practical reasons the downlink would be segmented into time frames as shown in order to simplify connectivity to a framed uplink structure discussed in the next section.)

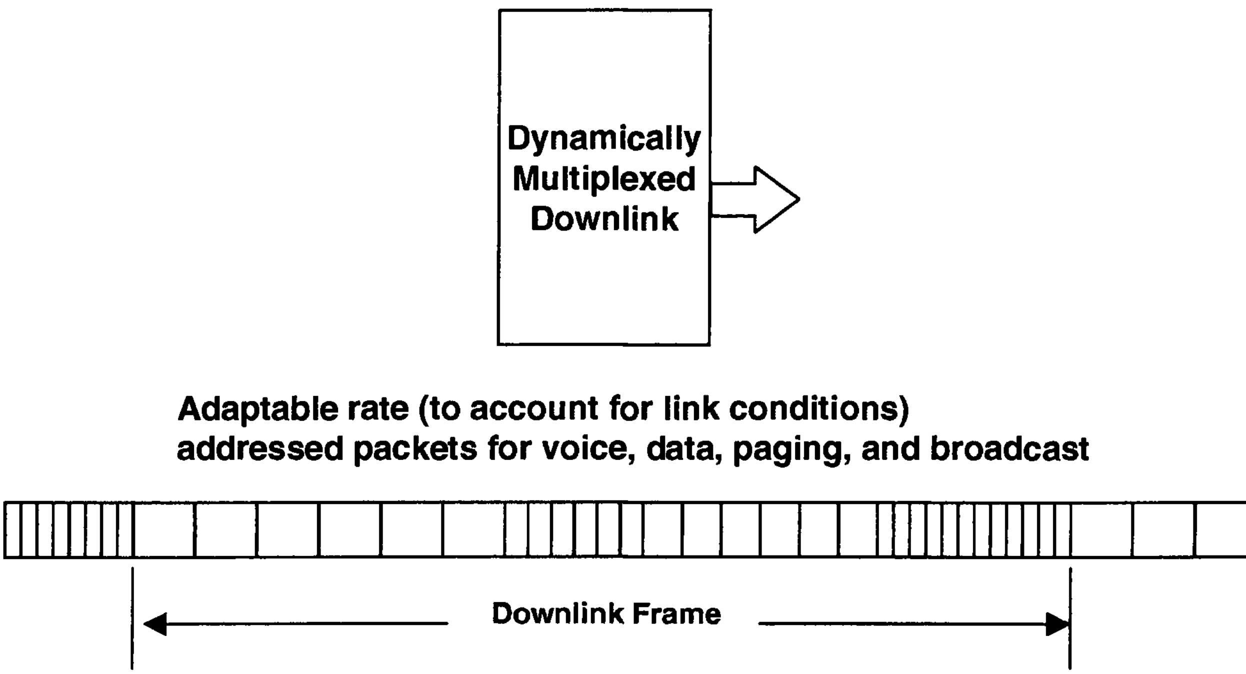


Figure IV-4 Downlink with Integrated Services

No matter how the downlink is formatted in detail, it should appear similar to a shared local area network medium with users able to selectively receive and process packets intended for them.

2. Uplink

Using the uplinks efficiently is a much more challenging problem. This is a result of the uplink users being relatively numerous with respect to the available receiving resources in the airborne node and thus efficient contention and assignments of these communications assets is the prime problem. End users must share the available uplink resources by using them only when there is actual data to send. This implies that there will need to be some version of demand access to the uplink channels. The difficult problem is to be able to predict reliably the actual data traffic profile. One solution is to reserve a "circuit" for the duration of a session. As noted previously, this is a very inefficient process, particularly for data communications, although it is reasonable to do this for streaming traffic such as voice. The other extreme is for the different users to transmit uplink packets (or cells) as soon as they are generated without scheduling

exclusive use of an uplink asset. However, this method can often result in different user's packets (or cells) colliding and thus not being received. The objective of any efficient uplink access scheme is to maximize utilization of each uplink channel while minimizing the collision between uncoordinated user transmissions and maintaining the desired QoS. The technique used could vary from pure ALOHA (transmit a packet/cell anytime when you have one and try again if there are collisions) to assigned time-slot and/or channel or anything in-between. In following sections, example implementations are discussed for this uplink assignment problem.

D. Approaches to Uplink Multiple Access

Providing efficient, responsive uplink multiple access will be one of the major design challenges. In this section approaches to this problem will be indicated, although design details and a performance analysis will be deferred to a later stage of the project.

A key objective in the design of the uplink (and downlink) is to provide the user with combined data and voice (or other streaming data) services with apparent simultaneity.

Because the uplink from an individual user will not be at as high a data rate as the downlink it is natural to use multiple uplink "channels" to accommodate multiple users simultaneously. These "channels" can be formed at the physical level by FDMA, TDMA, CDMA or various hybrids. In cellular telephony a channel is assigned to a user for the duration of a call. When dealing with bursty data communication the goal is to allow each channel to be rapidly accessed by whichever user needs the channel at the moment. In the ACN/HH system these uplink "channels" will be used for both bursty and streaming data.

There is a basic resource assignment strategy to decide upon. One can create a small number of rapidly shared high rate, e.g., 64 kbps, channels or a larger number of relatively low rate accesses that could be assigned to users for the duration of an interactive data session. The latter approach is akin to making a phone call and establishing a point-to-point protocol (PPP) connection for data communication . However unless the data rate per channel in this approach is about equal to the average rate of the session (usually less than a few 100's of bps) the connection will be used very inefficiently. Also, a data rate as low as the average rate can cause unacceptable delays when a burst, i.e., one or several data packets, is to be transmitted Hence the approach that will be concentrated upon is the efficient shared use of relatively high rate channels, up to 64 kbps, which are within the feasible range according to the link calculations of Section IV. (However, not all users will be able to support this rate at all times so a variety of lower rates, down to 2400 bps, should also be made available. At these very low rates a user could be assigned exclusive access for the duration of an interactive data session.)

1. A channelized uplink structure

A particularly desirable approach to use is a hybrid FDMA/TDMA channelization (as is used by the IS-136, CDPD and GSM commercial cellular systems). With appropriate synchronization this would create uplink channels that are orthogonal to one another. A sample structure to build upon is shown in Figure IV-5.

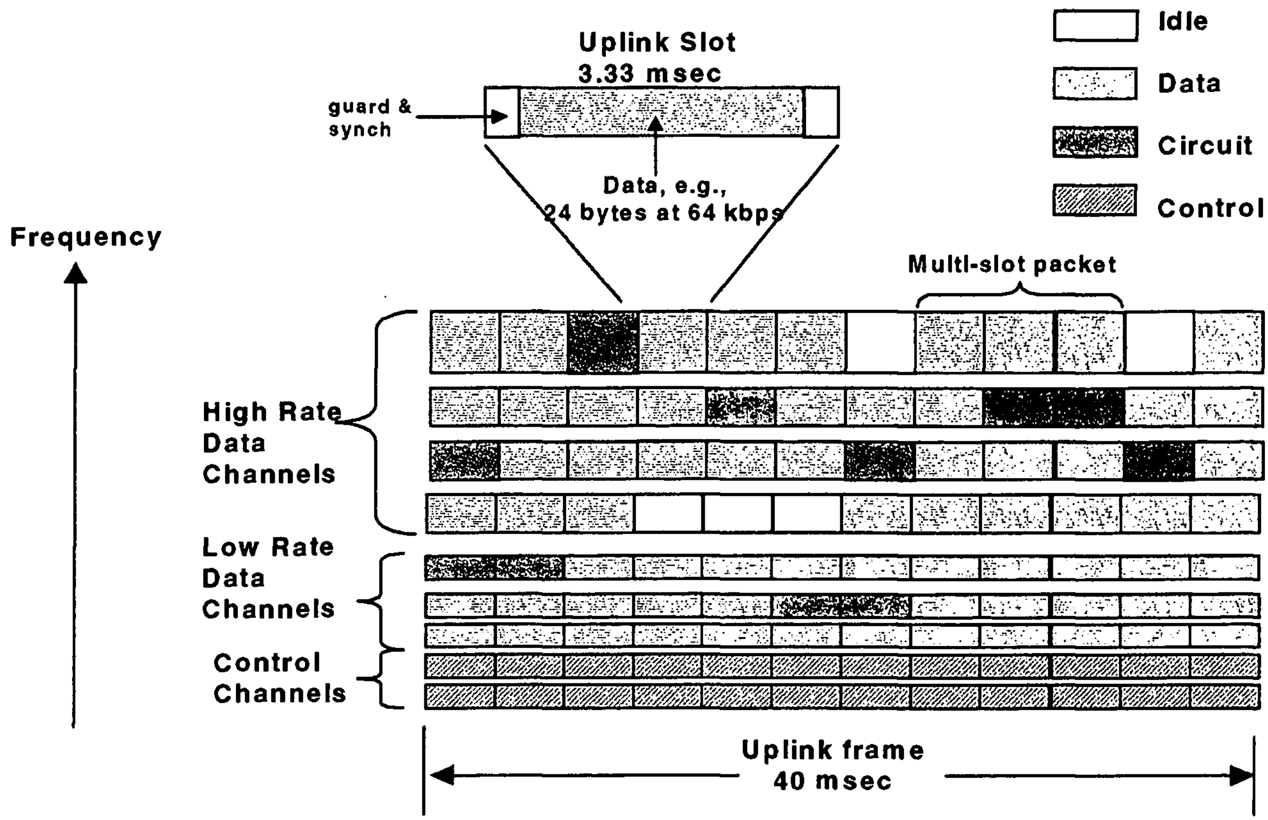


Figure IV-5 Uplink Signal Structure

The choice of frame time is critical. As an example of an appropriate frame time, 40 msec with 12 slots of duration 3.33 msec will be used for illustration. A user would transmit in one or several slots as discussed below. Frame times much longer would introduce undesirable delay for either voice or data due to buffering. Frame times much shorter may require impracticably short guard times per time slot for synchronization, settling times, and other overhead while trying to maintain efficient channel usage but can be considered. (In order to reduce the frame time which will lead to a more responsive behavior, interleaving schemes which amortize overhead functions should also be considered in a more detailed design. For comparison the GSM cellular system uses a basic frame structure of eight 577 μsec slots for a frame time of 4.6 msec; the IS-136 TDMA system uses six 6.67 msec slots in a frame of 40 msec.)

Most of the channels would be expected to be used for user data. At the system's nominal uplink maximum burst rate of 64 kbps, this would yield 24 data bytes per slot after overhead. Some of these high rate channels can be subdivided into a number of lower rate channels at rates of 32 kbps, 16 kbps and perhaps as low as 2400 bps, in order to accommodate disadvantaged users. Some low rate channels would also be used for signaling. (Signaling slots could also be provided in a time slot of the data channels for use by active users.)

Within each data channel it is anticipated that most of the slots would be used by packet data transmissions, which are emitted in bursts. However, voice or other streaming traffic can be assigned regularly spaced slots as shown. For example, a user having one slot per frame would be able to transmit at an average nominal rate of 4800 bps in a 64 kbps channel (or 2400 bps in a 32 kbps channel). This also allows an individual user to mix streaming and bursty data on its uplink.

If, for example, 32 channels of 64 kbps (or an equivalently larger number of lower rate channels) were provided this would accommodate up to 2.048 Mbps raw information. However, as will be discussed in the next section, the effective data rate will be lower in order to allow for rapid response multiple access.

The amount of bandwidth needed to accommodate these channels is about 4.1 MHz assuming a packing density of 0.5 bps/Hz. This 4.1 MHz signaling band would be spread over the entire RF bandwidth available. While frequency hopping or direct sequence spreading could be used, frequency hopping is recommended as discussed in Section IV. Individual users would hop in synchronism so as not to interfere with each other, each receiving the full hopping bandwidth protection as shown in Figure IV-6. If 10 MHz spreading bandwidth were available, each user would achieve a "processing gain" against jamming of 22 dB at 64 kbps and 36 dB at 2400 bps. (The hopping rate could be at the slot rate, 300 hops/sec or even faster for better protection if frequency synthesizer settling time can be kept small enough.)

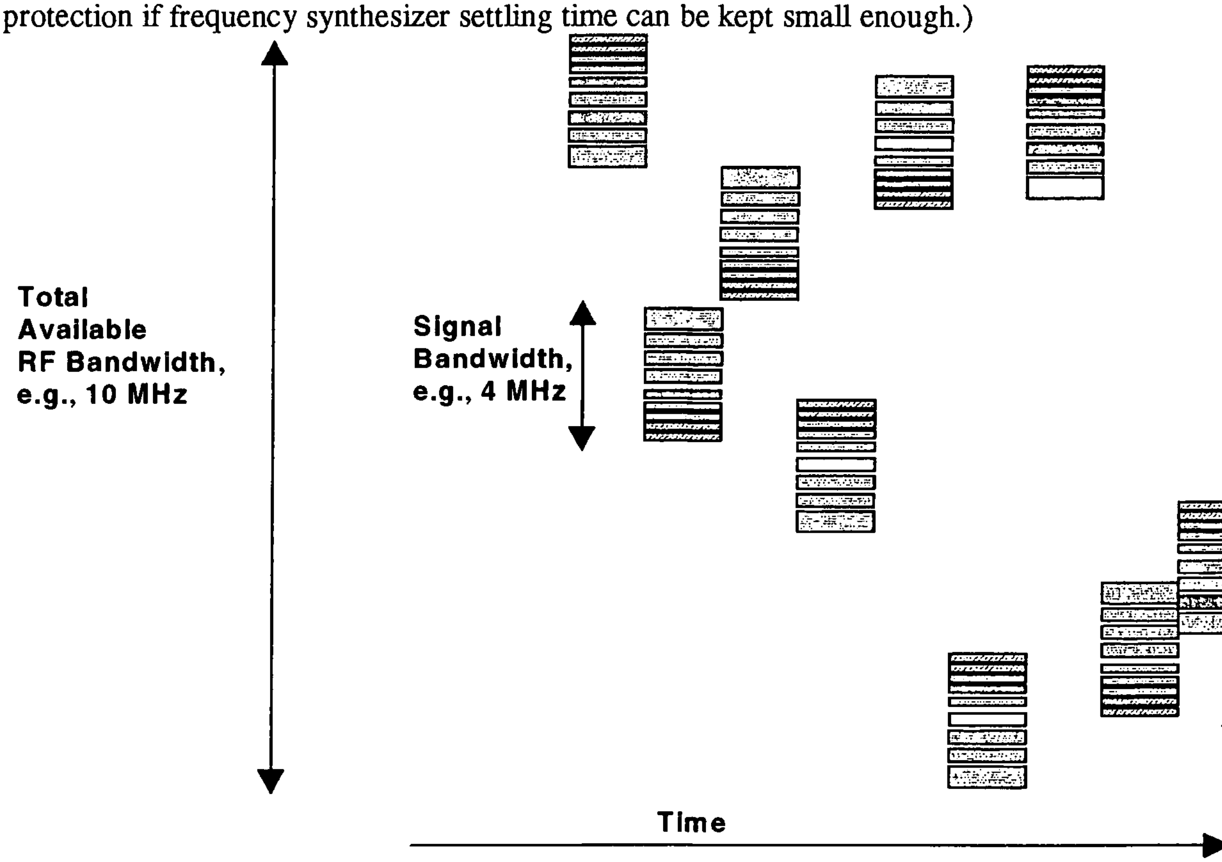


Figure IV-6 Uplink Frequency Hopping

2. Uplink access control

The means by which users obtain uplink access is critical in terms of system responsiveness (timeliness, assured access) and efficiency. Techniques include (1) pre-assignment of channels (the common technique of assigning a radio frequency to a conventional net of users); (2) the telephony-style circuit assignment on demand (as is used in cellular telephone systems); and (3) packet access (as with local area networks). All three types of access control can be available for use in the ACN system.

Pre-assigned channels can be accommodated in the suggested signal structure by allocating a certain number of slots per frame in a frequency channel. This scheme, should be used sparingly and only in the most constrained of situations, e.g., to serve very high priority users or streaming traffic. It is clearly the least flexible, efficient, and responsive.

Assigning channels (a number of slots per frame) in response to user demand is applicable to voice or other streaming services. This type of assignment can be given to an individual user, or a pair of half-duplex users in conversation or even a net of users which exercises its own push-to-talk protocol. Telephony protocols and signaling used in commercial cellular technologies can be used as a starting point for those needed by the ACN. However, a priority mechanism and adaptive channel features, e.g., data rate must be added.

The third mode, packet access is a good match to the type of access needed in bursty interactive computer-based transactions. Packet-oriented multiple access techniques have been the subject of extensive research and will not be discussed here in great detail other than to call attention to some relevant approaches. Analytical treatments can be found, for example, in [Bertsekas & Gallager] and [Pahlavan & Levesque].

Whatever approach is chosen, it will be worthwhile to take advantage of a topology where ACN operates as a centralized access control node. This is illustrated in the discussion of the two following example techniques. These examples are being presented to indicate some of the approaches that seem applicable. In the following examples only the slots available for bursty data are being discussed. It is assumed that the ACN uplink access controller has taken the streaming data slots out of the pool that can be used.

The analyses are greatly simplified and do not take into account all of the vagaries of the wireless channel. In particular, for discussion, the effects of channel errors are being put aside. In a full design all such issues would need to be carefully examined.

a) Digital Sense Multiple Access

"Digital Sense Multiple Access", DSMA (a variant of Carrier Sense Multiple Access, CSMA) is one applicable technique. Users send an End-of-Transmission flags to the ACN at the end of packet transmissions (or the ACN detects absence of signal) so the next slot can be determined to be available. The ACN then broadcasts this information on the high rate downlink. Users with data to send could then choose an available channel and begin transmitting in one of the available slots. If more than one user attempts to use the same slot on the same channel the ACN receiver would detect this conflict and broadcast this event in the following slot. A

contention resolution procedure is then put into play in which the colliding users attempt retransmissions at pseudorandomly selected times until one user is able to successfully complete transmission. (There are also somewhat more efficient ways of resolving these conflicts.) During this time no other users may attempt transmission on the channel. A commercial system using a similar approach is the Cellular Digital Packet Data (CDPD) overlay on the AMPS system.

DSMA is quite effective when packets are several slots long. This is illustrated in Figure IV-7. which shows the average transmission waiting time as a function of throughput for an average packet duration of 100 msec (equivalent to 800 bytes at 64 kbps). It is assumed that the packets have an exponential probability distribution. The TDMA slot duration is 3.33 msec long as in the example frame structure of Figure IV-5. For comparison the curves labeled "perfectly scheduled" show the total transmission time if the ACN could be perfectly informed of all pending packets and hence could schedule without collision on a first-come first-serve basis. Note that the DSMA result is only given for the single frequency channel case since that the only case where analysis has been available.

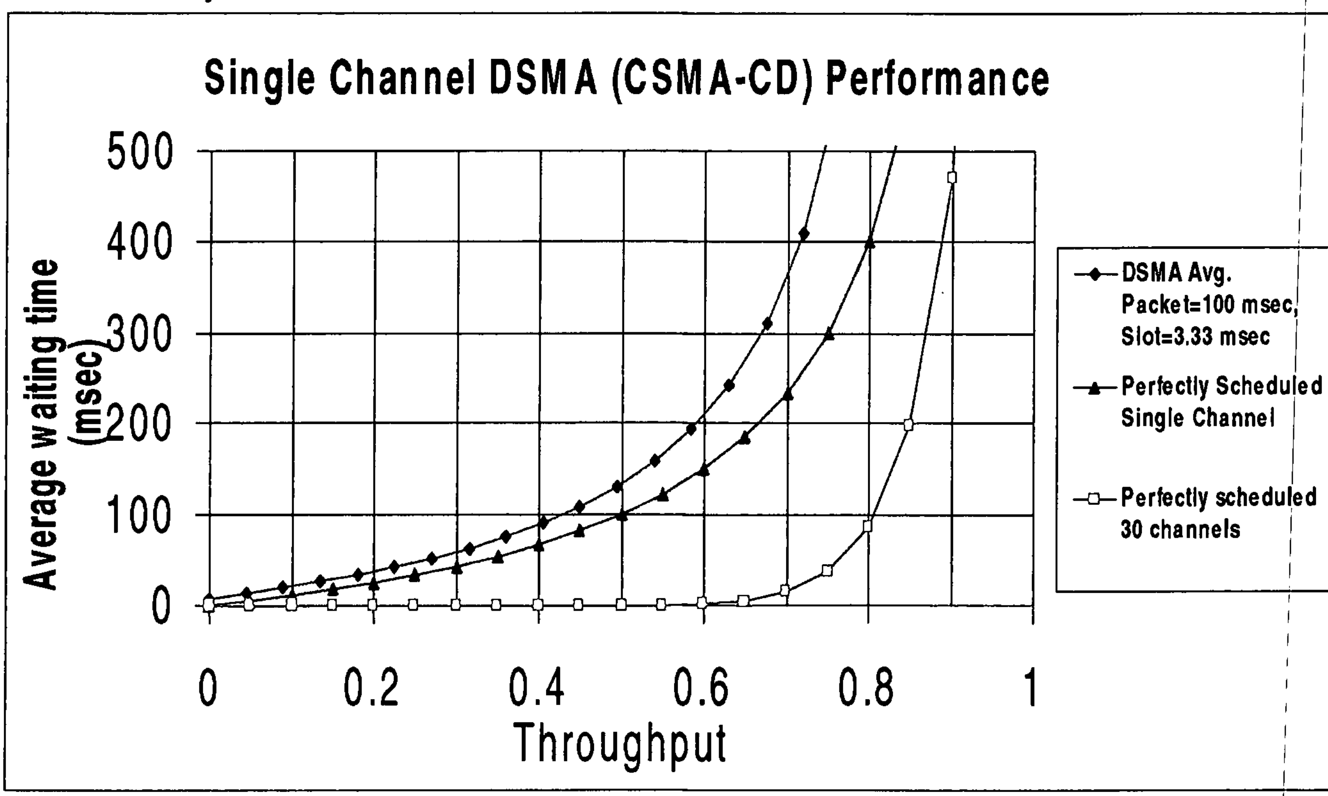


Figure IV-7 Message Waiting Time for DSMA (CSMA/CD)

The DSMA result shown in Figure IV-7 is adapted from the single channel CSMA/CD analysis of [Bertsekas & Gallager (Eq. 4.67)] and includes their adaptive strategy for optimizing performance. Based on their result, the average waiting time for a packet (to which transmission time must be added) would be given by:

$$Avg\ Waiting\ Time = \frac{2\rho + \beta(4.62 + 2\rho)}{2[1 - \rho(1 + 3.31\beta)]} T_{packet}$$

where ρ= the average throughput (or loading), T_{packet} is the average packet transmission time and β= the "idle time" as a fraction of an average message transmission time that it takes for the user to learn of a change in the state of the channel (idle, busy, or contention). In the case being analyzed, β is the ratio of a slot time to the average message time since it is presumed that the users can receive all state changes broadcast by the ACN in the slot immediately following the change even including propagation delays (less than 1 msec round-trip for 100 miles maximum range).

The results show several things:

- Average delay will increase with throughput (or loading), even with perfect scheduling, due to fundamental queueing dynamics
- Average delay will be reduced if more channels are in the available pool even for the same loading per channel (It is expected that this will also be true of a multi-channel DSMA strategy.)
- DSMA is a reasonably effective technique for providing responsive "random" access to the channel as long as the packet size is much larger that the slot time; its delay increases as packet size decreases because contention resolution time is a greater fraction of short message times. If the packet size is not much longer than the slot size, then performance will at best be equivalent to slotted ALOHA.

DSMA should be able to be adapted to work with multiple packet priorities by adaptively restricting slots for use by certain priority levels and/or restricting the lengths of time users can transmit in accordance with priorities.

b) Reservation channels and slots

Another basic approach to controlling packet access is to set aside some of the system bandwidth for use by low rate signaling channels and slots. This could be done by converting some of the RF bandwidth that could be used for data into a larger number of lower rate frequency channels. The slots on these channels could be used for sending requests for reserving data slots on the higher rate channels. Access to the reservation slots could be in an ALOHA-like manner, i.e., immediate transmission with randomly spaced repeats in case of collision, or assigned to users or a combination of the two.

Figure IV-8 shows some examples of how well this scheme might perform. Again, a packet duration, of 100 msec is used for illustration. Signaling overhead is set at 10% or less. For the single data channel case it is assumed that a separate signaling channel operating at a data rate of 10% of the data channel is created (thereby increasing transmission time to 110 msec). For the 32 channel case it is assumed that 2 high rate channels are converted into 6 low rate signaling channels, for an overhead factor of 7%. The signaling slots are 3.33 msec long as on the data channel and it only takes one signaling slot to convey a request. The signaling channels use a "stabilized ALOHA" strategy where the repeat probability is set adaptively by the ACN controller for optimum performance. The stabilized slotted ALOHA analysis of [Bertsekas and Gallager, Eq. 4.12] is used to estimate the delay. It is assumed that the ACN provides rapid feedback to users on whether the request was successful or not.

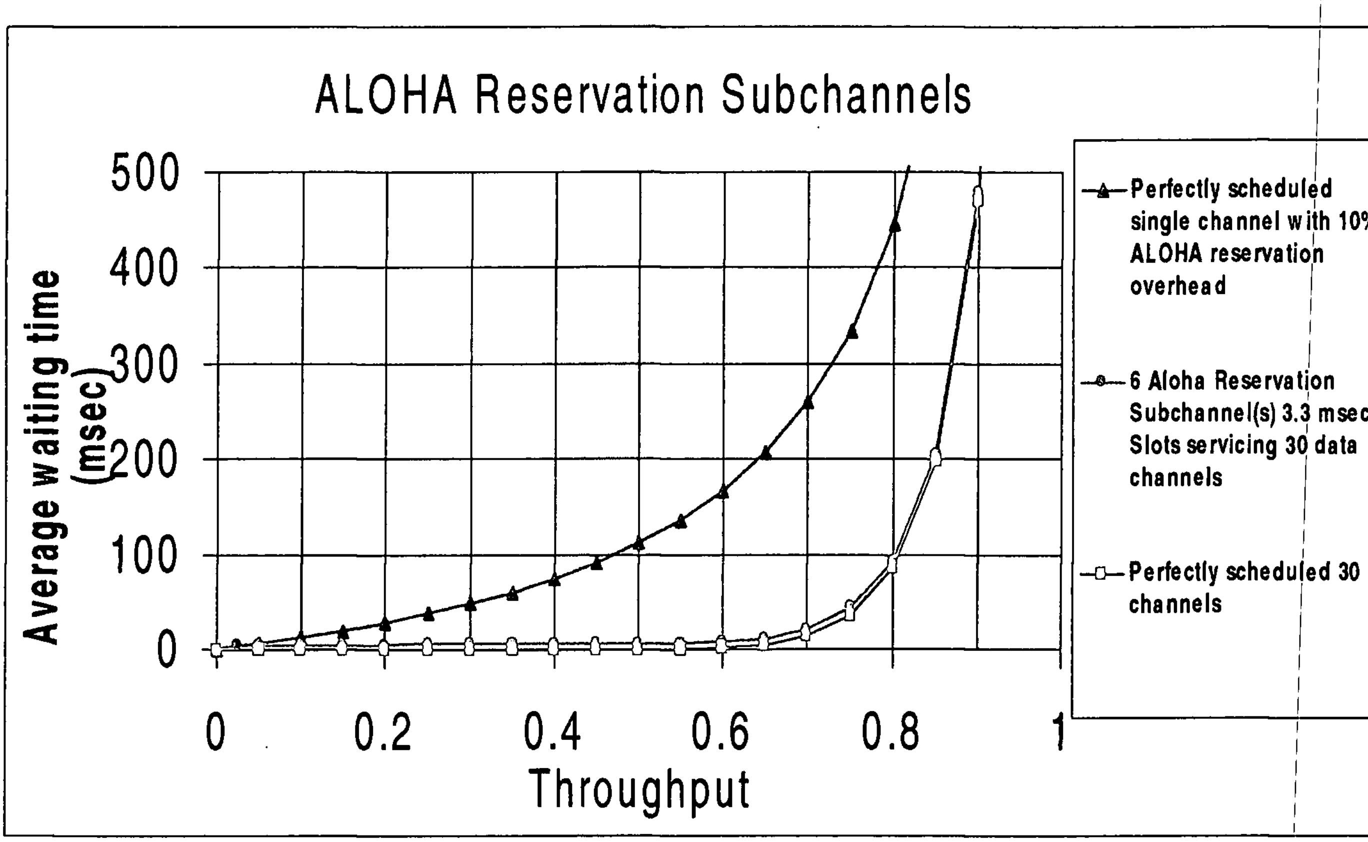


Figure IV-8 Message Waiting Time for Aloha Reservation Subchannels (100 msec average message length)

The results show that reservation channels and slots, even if used in an ALOHA scheme can be very effective. The total packet delivery time is seen to be close to the perfectly scheduled model. It also indicates that less overall overhead may be needed when servicing multiple channels.

It should also be added that there are a wide variety of ways to structure the request slots and channels. For example, a mixture of ALOHA and pre-assigned slots could be used which would guarantee that each user will have access to a request slot eventually. Slots could also be restricted to certain classes or priority levels of traffic. Adaptively adjusting the number of request channels and how they are used should also be considered.

Once again it should be noted that if the message length is short, then performance more akin to slotted ALOHA will result.

E. Network Interface Considerations

The Warfighter's Internet study examined many of the networking issues and functions that are associate with the ACN/HH. Here we summarize some of the main points.

From the point-of-view of the end user the ACN/HH should present an interface similar to a local area network, albeit with special features. This is illustrated in Figure IV-9. User

applications (which could include voice and video as well as computer-based applications) would interface through a well defined layered protocol stack. It is the responsibility of the ACN/HH subsystem to deal with the vagaries of the wireless link between the ACN and the handheld user device.

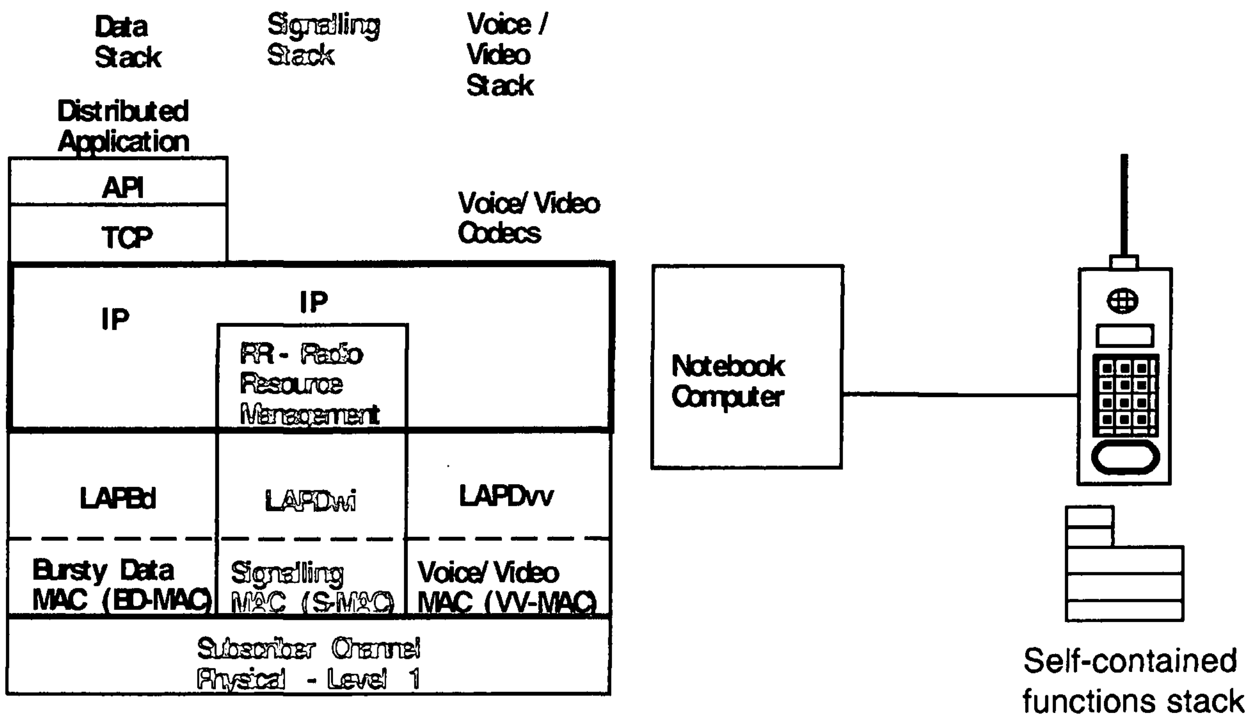


Figure IV-9 User Network Interface Example

On-board the ACN, the handheld subsystem would be able to interconnect with other on-board communication systems as well as other ACNs via crosslinks through an on-board switch-router (OBSR) that performs the essential routing functions. The handheld subsystem must provide the OBSR with mobile user registration information.

The handheld subsystem must also provide an ARP (Address Resolution Protocol) (functionally the same as is done in a wired Ethernet) in order to relate physical user channel parameters (frequencies and time slots) to user network addresses.

Note that the downlink from the ACN is a natural medium for efficient broadcast and multicasting. This capability is generally not exploited in wired networks, but would be a hallmark of the ACN/HH network.

It may also be necessary to support conventional circuit switched connections via the ACN/HH. It may therefore be necessary to include additional protocols to do this, but the essential structure recommended can readily incorporate these.

F. Duplexing Options

An important architectural design issue the selection of a duplexing technique, i.e., how to separate uplink and downlink signals. There are several options for doing so.

The architecture suggested in the previous sections is one that would work best with full frequency duplexing, i.e., with simultaneous transmissions on separate the uplink and downlink frequencies. This is most flexible because it allows uplink and downlink time slot assignments to be made with few constraints. Of course this puts a certain burden on the hardware design of both the terminal and ACN since good transmit-receive isolation must be provided. It also requires that a pair of spectral bands must be allocated. Whether the latter is a benefit or disadvantage is not clear. (AMPS and CDMA cellular systems use this approach.)

Another possibility is to use a slotted version of time-division-duplexing from the point-of-view of the handheld terminal whereby uplink and downlink time slots are assigned to a terminal on a non-interfering basis. (This technique is used, for example, in GSM where non-overlapping time slots are used for the uplink and downlink transmissions which are on different frequencies.) This technique eliminates the need for frequency duplexing at the handheld (but not at the ACN).

A third technique is to use full system time-division-duplexing whereby a time frame (several 10s of msec) is divided into uplink and a downlink partial frames. All transmissions are either uplink or downlink in each portion of the frame. (This technique is used by the Iridium satellite system.) Only one frequency band is required and no frequency duplexers are needed.) It is also possible to vary the amount of time given to uplink and downlink transmissions and hence an additional degree of freedom for an asymmetric system design is provided. Due attention would have to be paid to peak/average power trade-offs for both the ACN and handheld unit power amplifiers.

G. Examples of COTS and GOTS Similarities and Contrasts

Although there is no total COTS or GOTS system that corresponds to the architecture described above, many of its subsystems bear strong similarities to a number of COTS and GOTS technologies. It is reasonable to believe that ACN/HH subsystems might be patterned after their off-the-shelf analogs. Similarities and contrasts with several relevant technologies are listed below.

- The <u>GSM</u> cellular system employs FDMA/TDMA on its uplink (with an eight slot 4.62 msec frame at a burst rate of approximately 135 kbps including rate 1/2 coding). The uplink can use synchronized frequency hopping (at a rate of about 217 hops/second). However GSM is voice circuit-oriented, with essentially symmetric rate uplink and downlinks. (A packet system, GPRS (General Packet Radio Service), probably going to be added, but not of the asymmetric type.) The GSM signal structure may well serve as a model for the ACN uplink. Although GSM terminals are designed as time-duplexed symmetric units, the downlink could be utilized to operate at a total rate of 135 kbps, thus providing a degree of asymmetry.
- The <u>IS-136</u> AMPS overlay employs FDMA/TDMA on its uplink (with a six slot 40 msec frame at a burst rate of approximately 24.3 kbps including rate 1/2 coding). However IS-136

is voice circuit-oriented, with symmetric rate uplink and downlinks. The IS-136 signal structure may well serve as a model for the ACN uplink, although a packet access technique would need to be added. Although IS-136 terminals are designed as time-duplexed symmetric units, the downlink could be utilized to operate at a total rate of 146 kbps, thus providing a degree of asymmetry.

- CDPD (Cellular Digital Packet Data) is a commercial overlay over AMPS for packet data. DSMA is used as its uplink access technique, although it is employed on an uplink channel-by-channel basis and is therefore not as efficient as a multi-channel approach. The frequency channels are not hopped. The downlink operates at essentially the same rate as the uplink (approximately 10 kbps) but can be shared more efficiently. It has a protocol and signaling structures (in particular user registration and tracking combined with data routing protocols) that may well serve as a starting point for the ACN.
- The direct-sequence spread CDMA IS-95 cellular system is to be augmented with a packet data service (IS-707) that promises responsive data access without the need for a full-time circuit. Details of this new service were not explored in this study, but appear promising. [See http://www.qualcomm.com/news/pr980224a.html for a commercial announcement.]
- The Iridium mobile subscriber satellite system uses a TDMA/FDMA on its uplink and downlink (with an eight data slot 90 msec frame at a burst rate of approximately 19.2 kbps including rate coding). Half the slots are used for the uplink and half for the downlink on each frequency. However, Iridium is voice circuit-oriented, with essentially symmetric rate uplink and downlinks. The Iridium signal structure may well serve as a model for the ACN uplink, but a packet access technique would need to be added (this may be under consideration) and it is not frequency hopped.
- The Hughes DirecPC satellite system is an example of an asymmetric system with users having low rate "uplinks" by telephone line and a high rate (400 kbps) shared downlink via satellite. While the asymmetric and shared downlinks are highly similar to that suggested for ACN, the dedicated "uplinks" per user is an example of resource allocation that would be highly inefficient.
- Milstar is an example of an asymmetric on-board processing system. It employs a synchronized frequency-hopped variable rate FDMA/TDMA uplink with a full duplexed integrated variable high rate downlink. Although, Milstar is currently demand-assigned circuit-oriented there are advanced developments that will add an on-board packet-oriented switch in the future.

H. Transponder vs On-board Processing

Although a base station-centric approach with on-board processing is being recommended, it is still instructive to least consider some of the pros and cons of on-board processing versus transponders. While a transponder architecture may make sense for straightforward ACN relay applications, e.g., range extension for SINCGARS or MSE, it is not recommended for ACN handheld services. Justification for this recommendation is given here.

Two ways transponders could conceivably be used to support handheld services are discussed below.

1. Transponder to terrestrial base station

One possible use of transponders would be to relay all user uplinks to a terrestrial base station on a feeder downlink. A different feeder uplink would then be used to convey the downlink signals via a different transponder. This architecture is used, for example, in the Inmarsat, Globalstar and ICO-P satcom systems. It has the following pros and cons:

Pros

- potentially highest capacity since processing can be more extensive with complexity on the ground
- perhaps less hardware impact on ACN
- may work with available technologies (although protocol and timing changes may be needed)
- ground base station is a natural interface to terrestrial systems

Cons

- not autonomous
- requires terrestrial base station in coverage area or reachable by satcom link (which is not available on all potential ACN platforms and would have a long latency) or crosslinks if available
- requires high rate up and down backhaul links (although these might be shared with links to other terrestrial entry nodes)

Overall it is felt that the lack of autonomy with the need to be tethered to a terrestrial base is a serious compromise of the ACN mission which itself is supposed to provide instant infrastructure.

2. User-user transponder

The other potential use of transponders is to provide direct user-to-user connectivity (as is planned for SINCGARS and other legacy radio range extension). The pros and cons of this arrangement are:

Pros

- potentially simple ACN realization
- extension of netted radio for voice and similar "private" networks

Cons

- requires either pre-assigned resource allocation, or complex distributed demand assignment system for efficient use of resources, and/or terrestrial base station
- inflexible intra-system connectivity, e.g., multicasting and broadcasting will be difficult and/or inefficient

- does not provide asymmetric services
- power balancing difficulty greatly reduces capacity for users sharing a transponder but could use multiple transponders at cost of complexity
- requires "gateway" for interconnectivity with other systems

It is strongly recommended that this architecture not be pursued, as it not efficient for the types of data services envisioned for the ACN.

V. Link Performance Factors

This section presents a summary of the factors that will determine system performance, e.g., data rate, range, capacity and anti-jamming protection. It begins with basic free-space link calculations and then discusses performance loss mechanisms that must also be considered.

The results will shown show that useful data rates can be established at long ranges under the stated assumptions including 15 dB of propagation losses. However, it should be understood that there is no single number that completely describes the effect of the loss mechanisms and the figure of 15 dB was chosen to representative a conservative, but not all-inclusive value. From a system design point-of-view it seems more realistic to work with a reasonable loss figure for nominal operations and to include a variety of techniques that would allow for graceful degradation in the face of increased losses. Techniques that can be designed in from the beginning include variable- rate modems, channel performance monitors, smart, adaptive ARQ algorithms, and adaptive source compression. In addition, the use of antenna technology on the ACN which can provide multiple high gain beams (or sectors), possibly with adaptive interference rejection, can have high leverage in increasing performance.

A. Free-space link calculations

Free-space link calculations can be used as the starting point for determining the relationship among physical parameters such as operating range, operating frequency, transmitter power, antenna gain and noise environment.

When the link is operating in the presence of additive white Gaussian noise the supportable data rate, R, in bps is given by

$$R = (P_r / N_0) / (E_b / N_0)_{req}$$

where P_r is the received power, N_0 is the receiver noise power density, and $(E_b/N_0)_{req}$ is the required signal to noise ratio per bit for the modulation/ coding scheme employed. The received power is calculated from the transmission equation,

$$P_r = Loss(f)*P_t\, G_r\, G_t(\theta)\, [(c/4\pi)*(\sin(\theta)/ h)*(1/f)]^2$$

where Loss(f) accounts for the attenuation loss (which is a function of frequency), P_t is the transmitter power, G_r is the receiver antenna gain, G_t is the transmitter antenna gain, θ is the angle measured from the ACN horizon ($\theta = \pi/2$ is nadir), c is the speed of light, h is the altitude of the ACN and f is the operating frequency. (A flat earth approximation for range is being used; the geometric error is small for cases of interest.)

As a starting point the antenna pattern used for the ACN will be assumed to have an idealized $\csc^2(\theta)$ shape. This pattern is chosen because, mathematically, it exactly compensates for the increased space propagation loss to users as a function of range. After normalization the gain of this idealized antenna expression is given by

$$G_t(\theta) = [2*\sin(\Theta)/(1-\sin(\Theta))] * [1/\sin^2(\theta)]$$

where Θ is the angle to the maximum range of interest. This equation is found by setting the gain proportional to $1/\sin^2\theta$ over the angles from nadir to the maximum range and equal to 0 elsewhere. The proportionality constant is found by normalizing the gain expression to the total power radiated by the antenna. As an example, if the ACN is at 65000 feet and the maximum range is 100 miles, then the maximum antenna gain would be 12.7 dB towards the horizon and -5.6 at nadir. (A -5 dB factor will be included in the link calculations below to account for the inability to achieve the ideal antenna pattern.) Note that when the previous two equations are combined the $\sin(\theta)$ dependence cancels, and the received power is proportional to $1/\text{frequency}^2$ and is not a function of the distances from the ACN. Thus all users in the antenna coverage area can achieve the same data rate in the absences of other link losses. An unfortunate fact is, however, that most users are likely to have a low elevation angle with respect to the ACN and will be subject to serious terrain-induced path loss degradations. Figure V-1 is a plot of elevation angle versus range.

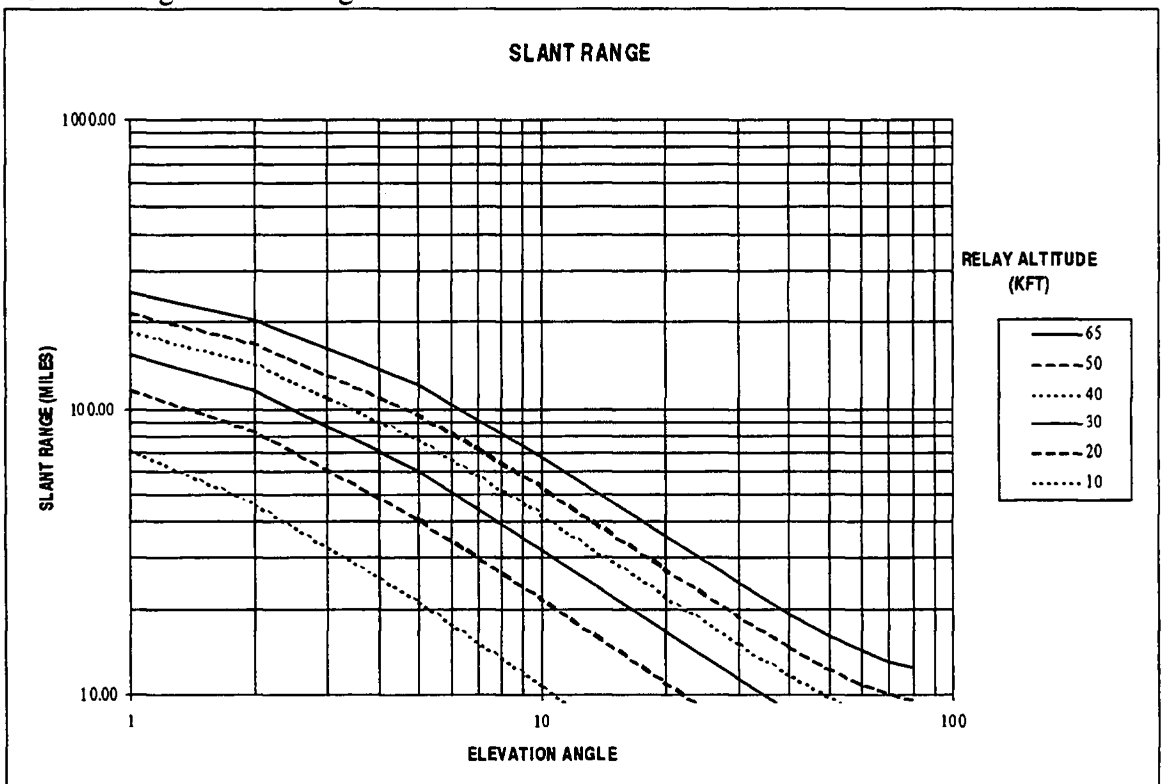


Figure V-1 Elevation Angle vs Slant Range

The following assumptions will now be made in performing the link calculation with results shown in Figure V-2 and Figure V-3:

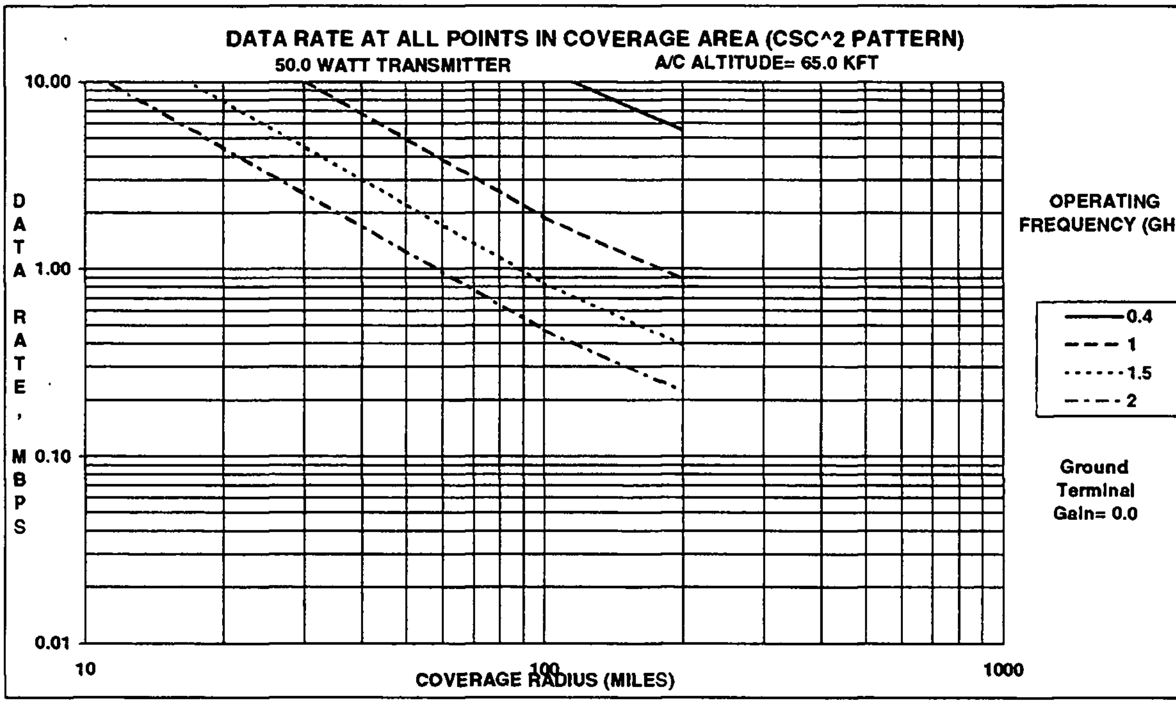
- the altitude of the ACN is 65,000 feet.
- the antenna gain of the handset is 0 dBi.
- the pattern of the antenna gain on the ACN varies as $\csc^2$(depression angle), i.e., it compensates exactly for range losses that vary as $(\text{distance})^{-2}$

- the antenna gain on the ACN is reduced by 5 dB to account for variations from the ideal pattern
- 1/distance^2 free space path loss
- there is 3 dB loss between the transmitter amplifier and the transmit antenna
- the receiver noise temperature of both the handset and the ACN is 500 K (including background and low noise amplifiers used by the receiver)
- the required signal to noise ratio of the received signal, $(E_b/N_0)_{req}$, is 8 dB for reliable communication
- 15 dB of loss was deducted from the link calculation to account for blockage, fading, attenuation, and multipath; this will be addressed in the next sections
- only background noise is taken into account; multiple access and other forms of interference are assumed to be negligible

Figure V-2 shows the link calculation for a 50 W transmitter which is in the range of what might be used on the downlink for the aggregated data and voice services. Figure V-3 shows the link calculations for a 3 W transmitter which is a reasonable peak power for the handset. The transmitter powers indicated should be interpreted as peak (or average) powers and the data rates are correspondingly peak (or averaged). (In the case of the handset, the uplink is expected to be bursty or time division multiplexed; hence the average uplink power needed during a data or voice session would be less than the peak by a factor equal to the transmit duty cycle. The average uplink data rate would correspondingly be lower. The ACN transmitter would be expected to be on nearly full duty-cycle.) In these figures the data rates shown are available for the entire coverage area within the indicated maximum ranges because the antenna pattern is readjusted depending on the desired coverage area.

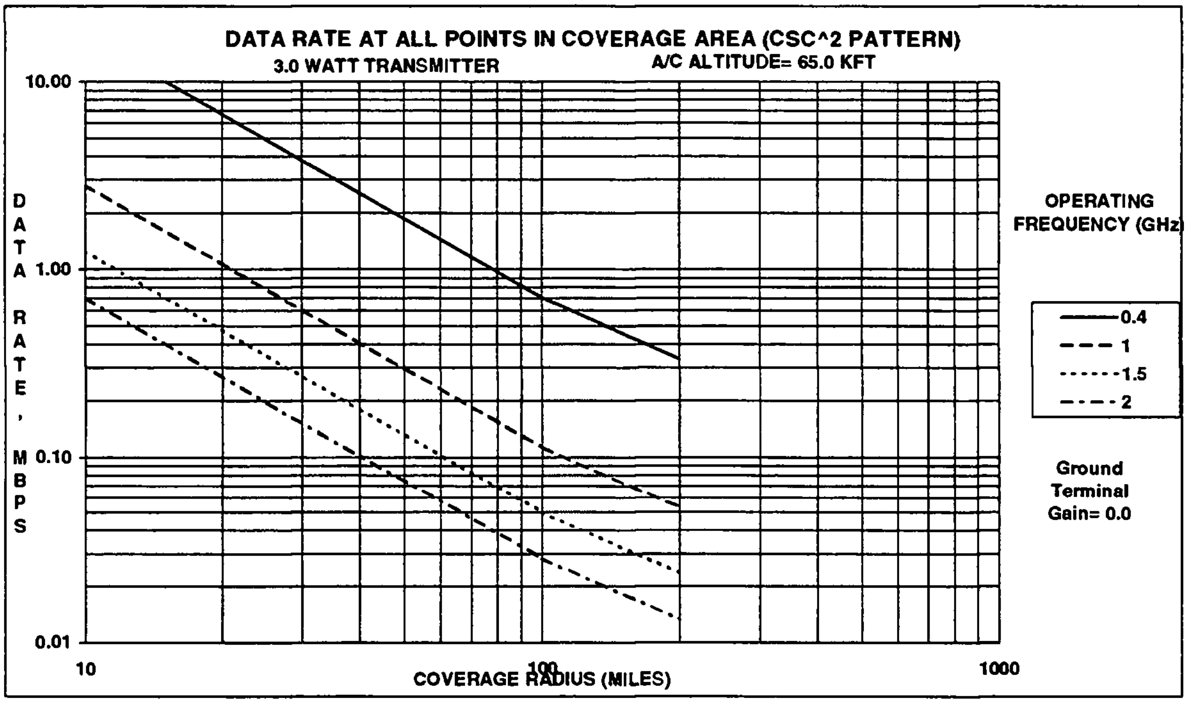
The results show that:

- the desired data rates (10's of kbps burst rate on the uplink, a few Mbps on the downlink) should be possible with the given parameters with a coverage area of 100 mile radius from the ACN at an operating frequency of about 1 GHz or below
- performance is better at lower frequencies (under the assumption that the antenna gains are independent of frequency for a given coverage area; it takes a larger antenna to achieve this at lower frequencies)
- alternatively, at lower frequencies, e. g., around 400 MHz or below, it should be possible to achieve the indicated performance with simpler ACN antennas or with greater link margins



			FOR MAX RANGE=	100	MILES
(EB/N0)req	8	DB	IDEAL GAIN AT NADIR	-5.6	DB
RX SYSTEM NOISE TEMP.	500	DEGREES, K	IDEAL GAIN AT MAX RANGE	12.7	DB
MARGIN OVER FREE SPACE	15	DB	ALLOWANCE FOR NON-IDEAL A/C ANTENNA PATTERN	-5	DB

Figure V-2 Downlink Data Range vs Coverage Range



		FOR MAX RANGE=	100 MILES
(EB/N0)req	8 DB	IDEAL GAIN AT NADIR	-5.6 DB
RX SYSTEM NOISE TEMP.	500 DEGREES, K	IDEAL GAIN AT MAX RANGE	12.7 DB
MARGIN OVER FREE SPACE	15 DB	ALLOWANCE FOR NON-IDEAL A/C ANTENNA PATTERN	-5 DB

Figure V-3 Uplink Data Rate vs Coverage Range

B. Path Loss Degradations

Path loss mechanisms include: shadowing of the signal from nearby buildings, hills and mountains; attenuation of the signal by the atmosphere, foliage, building walls, and the human body; and reflections of the signal from the ground and other nearby objects. Many of these losses are similar to the losses experienced in land mobile radio (cellular telephony); however, there are some differences. This section gives more detail about these loss factors.

One way to characterize the loss mechanisms is to investigate how far the handset must be moved to bring about a change in the loss. On the longest scale (miles) is the effect of the free space propagation loss between the ACN and the handset. This factor sets the median or average value of the received signal strength. In descending order of distance scale are the effects of: reflections from distant objects such as mountains, attenuation losses, multipath reflections from buildings and nearby objects, obstacle blockage, reflections from ground bounce, and interactions with the operator or vehicle.

1. Multipath Effects

In terrestrial communication systems, the received signal rarely contains only a single component which is received directly from the transmitter. Most often the received signal contains the directly radiated signal plus indirect signals that are reflected from the ground and/or other objects. The net effect of reflections from nearby objects, referred to as multipath, is very sensitive to the location of the handset. The ground bounce component will be discussed separately.

The effect of multipath in the ACN/HH system will be similar to that in land mobile radio. In typical urban/ suburban environments, if the received signal strength is recorded as the handset is moved within a cubic volume one wavelength on a side, there will be many peaks and nulls in the signal level. The level will typically be within +10 dB and -30 dB of the median or average value. There is a frequency dependence to the multipath phenomena. At higher frequencies (~ 1 GHz and above) most objects will cause reflections so there are many signal paths adding in and out of phase at the handset. At lower frequencies (VHF), the objects must be larger (> several meters) to cause reflections. Thus in a given situation, there are fewer signal paths to the receiver at lower frequencies, so the rapidity of the peaks and nulls is less. When one or both ends of the links are in motion the net effect of this multipath is to cause nearly Rayleigh fading statistics. When there is a single path that dominates the total, the fading statistics are termed Rician.

Multipath models, particularly those used for relatively wideband systems are best described in temporal terms. Some of the multipath models used by the cellular industry are described in [Pahlavan & Levesque, Chapter 6]. They show multipath ray delays that range to about 50 μsec (corresponding to about 10 miles). These models may be used as a starting point for an ACN propagation model, but clearly would need to be extended for the longer ranges available to an airborne platform.

Spread spectrum systems can deal quite effectively with frequency selective fading due to multipath when the significant multipath delay times are greater than about 1/(spread bandwidth). If the spread bandwidth is greater than about 10 MHz, then multipath components that are delayed greater than about 0.1 μsec (corresponding to about 100 feet) should not cause serious degradation to a well-designed system.

2. Shadow Fading

Shadow fading arises from shadowing of the handset by nearby buildings, hills, and mountains. In the ACN/HH system this effect will likely be similar to that observed in land mobile radio where it has received much attention. The observed received signal levels as the handset is moved along an arc at a constant radius from the base follow an approximately log-normal distribution. In typical urban/suburban environments the standard deviation of the distribution in signal strength is 6-8 dB. There is a frequency dependence to the magnitude of these deviations, since the lower frequencies tend to diffract around moderate size objects where higher frequencies tend to have more definite shadow regions [Parsons]. Additional attenuation may also be caused by blockage or proximity to the human operator.

3. Foliage Attenuation

Foliage attenuation is an important and difficult problem in mobile communications. It is difficult to formulate accurate models that can be generally applied because the topology and the types of vegetation are too varied. However, there are simple models of foliage attenuation which give a sense of the magnitude of the phenomenon.

In the frequency range of 300 MHz to 2 GHz, the modified exponential decay (MED) model illustrates the problem [Weissberger]. The attenuation due to propagation through dense, dry, in-leaf trees is given by

$$L = 1.33 * F^{0.284} * d_f^{0.588} \qquad \text{for } 14 \le d_f \le 400$$
$$= 0.45 * F^{0.284} * d_f \qquad \text{for } 0 \le d_f \le 14$$

where L is the loss due to the trees in dB, F is the frequency in GHz, and d_f is the depth of the trees in meters. For the conditions shown in Figure V-4 (10 meter stand-off distance from 10 meter tall trees) it is seen that foliage alone can cause considerable attenuation at low elevation angles, although it is less of a problem at lower frequencies. (For reference, with the ACN at 65,000 ft., 90% of the coverage area will view the ACN with an angle between 7 and 20 degrees, corresponding to a maximum range of nearly 100 miles.)

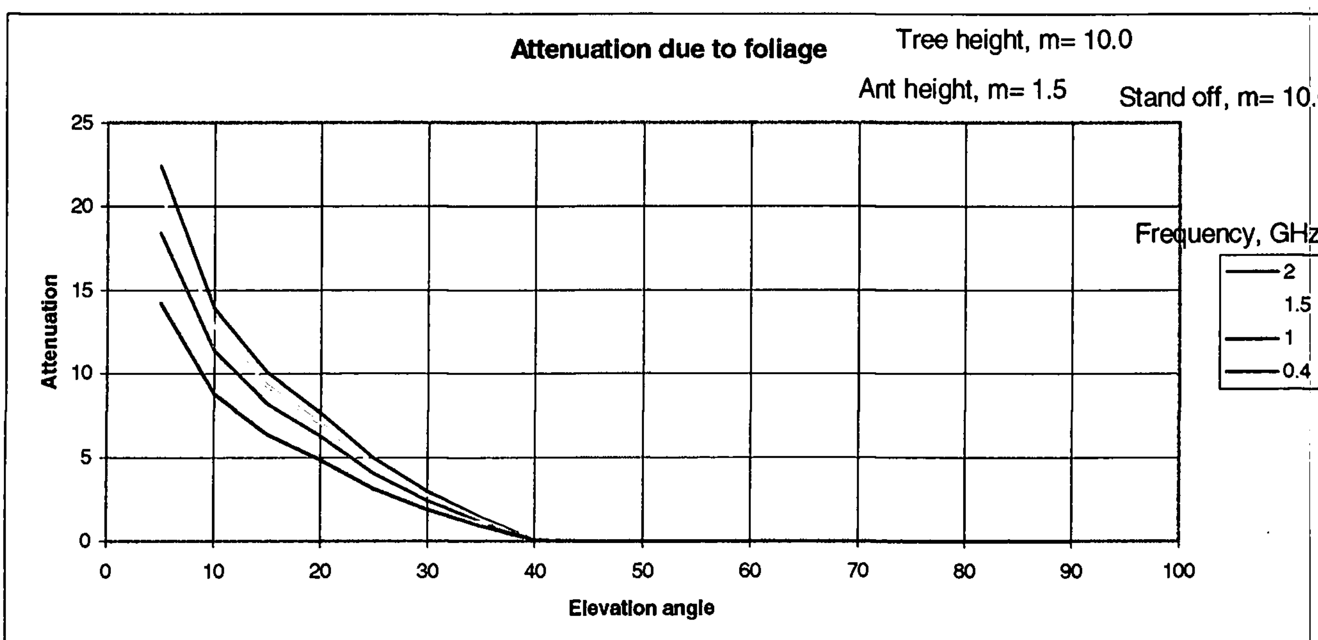


Figure V-4 One Foliage Scenario (Tree height=10 meters, stand-off distance=10 meters, handheld antenna height=1.5 meters)

4. Ground Reflection Effect

The effect of the reflection from the ground is different in the ACN system than in land mobile radio. In land mobile radio, the base station antenna is only a few hundred feet above the Earth so the path lengths and signal strengths of the direct signal and the ground reflected signal are nearly identical. Since the phase of the signal reflected from the Earth is shifted by 180 degrees, these signals add destructively. It is straightforward to show that the combined signal strength decreases proportional to $1/\text{distance}^4$ rather than $1/\text{distance}^2$ as in free space propagation.

The ACN will loiter at a nominal altitude of 65,000 feet which gives rise to longer path length differences between the direct signal and the ground reflected signal. Thus the ground reflection behaves more like a multipath signal changing with relative position of the handset rather than being independent of the handset position as in the land mobile radio case. Figure V-5 shows the relative signal strength at the handset as a function of the distance from the ACN. In this calculation the ACN is at 65,000, the handset is at 5 feet, and the operating frequencies are 500 MHz and 1.5 GHz. The figure shows that there are nulls where the signals add destructively and that the spacing between the nulls is a function of frequency. However, the general trend is that the signal strength decreases proportional to $1/\text{distance}^2$ and not as $1/\text{distance}^4$.

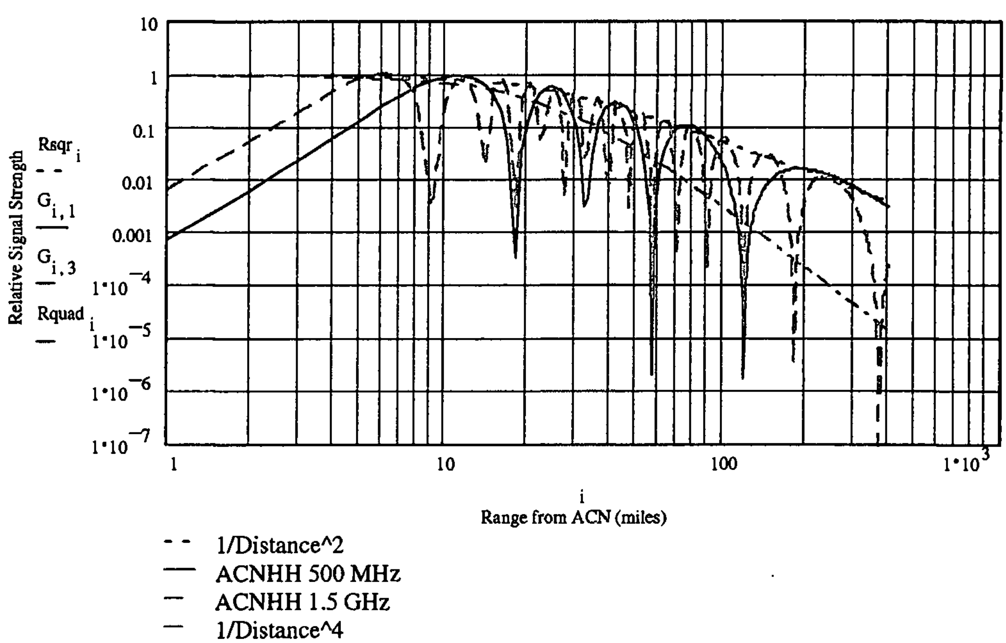


Figure V-5 Relative Signal Strength for the Handheld System versus Range (unobstructed direct path and ground bounce)

5. Height of the Handset Antenna

The height of the antennas also affects how the direct and Earth reflected signals add. Figure V-6 shows the relative signal strength versus the height of the handset above the Earth. The ACN is at 65,000 feet, and the frequencies are 500 MHz (wavelength ~2 ft.) and 1.5 GHz (wavelength ~ 8 in.). The plot shows the relative signal strength will vary substantially within a 3 foot cube. Thus there will be local "sweet" spots where the reception will peak. The plot shows the variations in reception as the antenna is raised from 3 feet to 6 feet above the Earth for two ranges from the ACN: 25 miles and 75 miles. The distance between the nulls is a function of the operating frequency and the distance from the ACN. Directly beneath the ACN the distance between nulls is 1/2 wavelength. Away from the ACN the nulls are spaced further apart. At 25 miles the nulls are about one wavelength apart, and at 75 miles the nulls are about 3.5 wavelengths apart. The more rapidly varying signal strength of the higher frequency signal is evident.

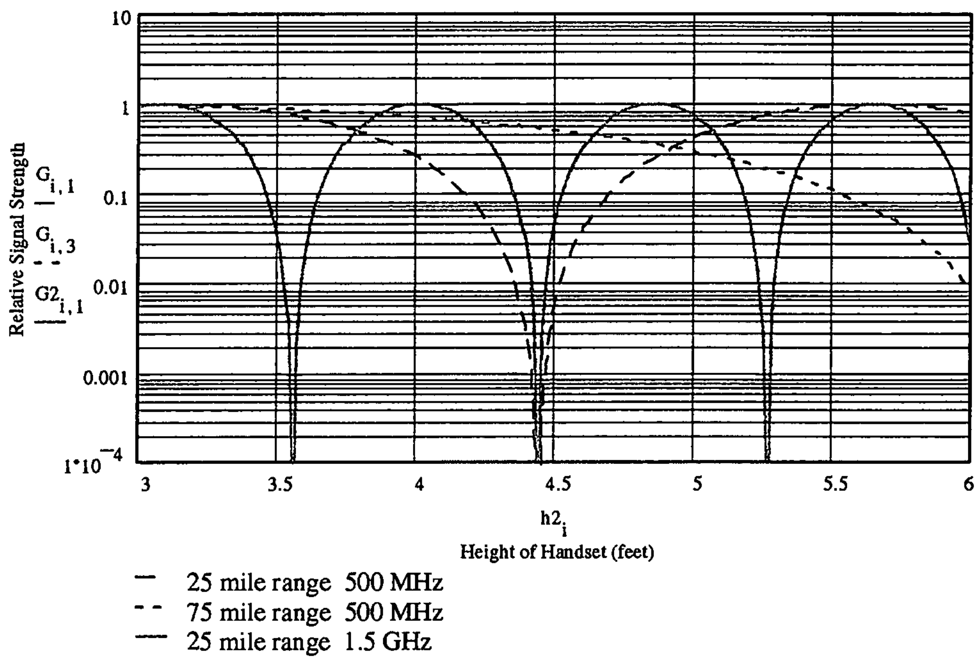


Figure V-6 Relative Signal Strength for the Handheld System versus Height of Handset (unobstructed direct path and ground bounce)

The final plot in this sequence, Figure V-7, is the relative signal strength versus the operating frequency. In this plot the ACN is at 65,000 feet; the height of the hand set is 5 feet; and the distance between the two is held constant. It is seen that the direct signal and the ground reflected signal add in and out of phase as a function of frequency. The cause of this behavior is relatively straightforward. The difference in propagation time (differential path delay) for the two paths is constant (because the difference between the two path lengths is constant). There are frequencies such that, for the given differential path delay, the two signals add in phase (or out of phase). As the frequency changes, and thus the wavelength, the two signals no longer add in phase (or out of phase). At twice the original frequency the two signals add in phase again (or out of phase). Thus the periodicity in frequency is determined by the inverse of differential path

delay. Since the differential path delay decreases as the range from the ACN becomes larger, the nulls stretch out at greater distances from the ACN, as shown in the figure.

This phenomena is relatively independent of frequency since the ground reflection is relatively independent of frequency. It is, however, a relatively strong function of the distance from the ACN and the height of the handset. As the distance from the ACN increases or the height of the handset decreases, the differential path delay decreases. Thus the bandwidth between nulls (or the bandwidth of the null) increases. At a 100 mile range with the handset at 5 feet above the ground, the bandwidth between nulls is approximately 800 MHz.

The consequence of the received signal strength nulls versus frequency is significant because is shows that it is impractical to use a spread spectrum technique to overcome the null which arises from the ground bounce. The bandwidth of the signal must be larger than the nulls in the frequency domain, which would require a signal with several hundred megahertz of bandwidth.

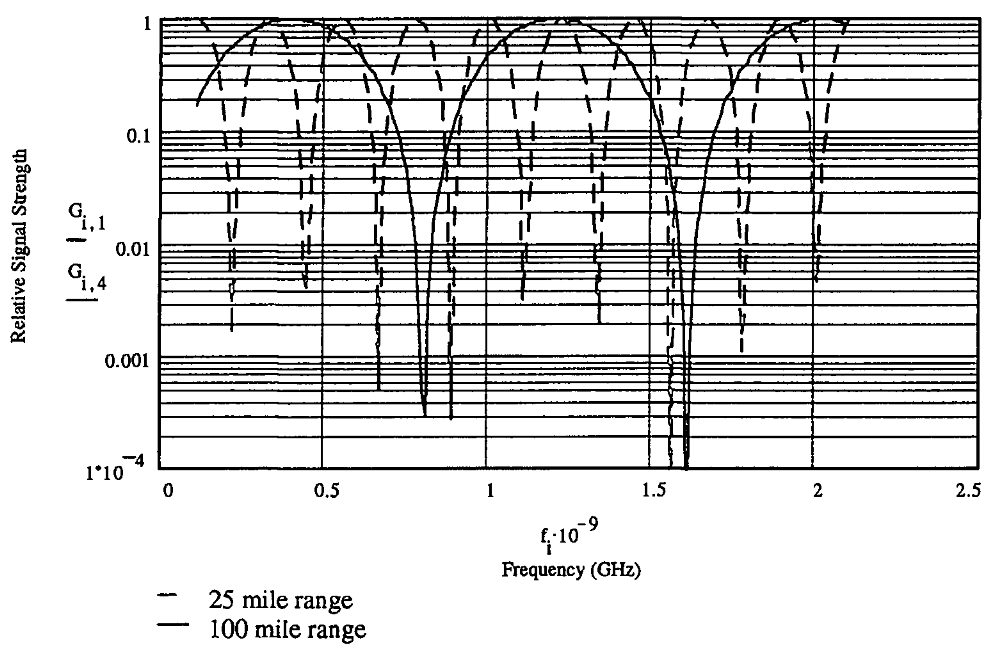


Figure V-7 Relative Signal Strength for the Handheld System versus Frequency

C. EMI

The performance of the system will also be directly affected by the electromagnetic interference (EMI) environment in which it must operate.

On the ACN uplink EMI can come from:

- on-board ACN radios transmitting in or near the uplink handheld band
- intermodulation products caused by multiple ACN transmitters
- ground based transmitters in or near the uplink handheld band (friendly and enemy communicators and/or jammers)
- handheld user transmissions intended for other ACNs

There is a similar list for EMI that would affect the handheld downlink.

Some EMI is similar to additive gaussian noise, e.g., out of band noise from transmitters. The effect of this type of EMI is readily determined since it simply adds to the receiver noise level.

Other EMI could be pulsed, frequency selective or have other decidedly non-gaussian characteristics. The effect of such noise can not be generally quantified. However, there are a number of techniques for mitigating its effects of all EMI including:

- antenna placement
- antenna pattern steering
- excision techniques (not effective against gaussian EMI)
- frequency hopping (and frequency avoidance) spread spectrum (helpful against frequency dependent EMI, e.g., narrowband interference)
- other forms of spread spectrum (depending on the form of EMI)

Any or all of these techniques may be required for the ACN handheld system and is a major issue that needs to be addressed. The ACN EMI study has addressed some of the important antenna placement issues and has characterized the performance of selected other on-board ACN systems in this regard.

D. Capacity

The capacity of an individual ACN can be measured primarily by the total data rate it is able to receive, process and convey to downlink users with an acceptable quality of service. Quality of service will enter into the measure because, for example, it may determine how many simultaneous uplinks must be available in order to keep delays and blockage probabilities to an acceptable level. It is difficult to cite a single capacity number because the links to and from individual users will vary so widely. However, it is possible to come up with a nominal figure for a total capacity of a node in order to size the hardware capability needed, but recognize that operating conditions will determine the performance of links to individual users.

The prime factors that will enter into determining capacity will be:

- signal-to-noise ratio of individual uplinks or downlinks
- bandwidth availability and spectral efficiency (bps/Hz) of multiple access waveforms
- space, power and weight constraints of ACN and user equipment

The first two issues will be briefly discussed below. The third will be discussed in the section on Implementation.

In addition, account must be taken of the possibility that an ACN will be operating in concert with other airborne platforms and hence its capacity will also depend on interference from adjacent airborne nodes and their users.

1. Signal-to-noise ratio

Section V-A presented link calculations that showed the feasibility of 64 kbps uplinks and about a 2 Mbps downlink using 3 watt and 50 watt transmitters respectively at frequencies in the range of 1 GHz using a single csc^2 shaped ACN antenna beam and an allowance for losses of 15 dB out to a range of 100 miles. The primary capacity limitation is the signal to noise ratio of the downlink (since uplink capacity can be increased by supplying more demodulators) and Figure V-2 shows the relationship.

Downlink capacity can be increased by increasing the ACN downlink EIRP by increasing transmitter power and/or using a higher gain antenna, e.g., by sectoring.

For example, using a 50 watt downlink transmitter would result in a nominal capacity of 3 Mbps which could include a 1.5 Mbps tactical broadcast, plus 200 voice circuits at 2400 bps, plus 1 Mbps of user data traffic.

2. Spectral efficiency (bps/Hz) of multiple access waveforms

Spectral efficiency contributes to system capacity even with the use of spread spectrum, wherein the RF bandwidth is much greater than that just needed for data transmission. The use of spectrally efficient multiple access waveforms will permit the use of (nearly) orthogonal signals to be used by multiple airborne platforms and/or within multiple antenna sectors of the same platform. As already indicated, a desirable way to implement this is with synchronized frequency hopping in conjunction with FDMA/TDMA.

It is particularly advantageous to use orthogonal waveforms on the uplink to an individual ACN. If non-orthogonal waveforms are used then all users appear as "noise" to all the other users and it is well known that the spectral efficiency in this case will be no better than $1/(Eb/No)_{req}$ bps/Hz. After the common allowance of -2 dB for imperfect power control this would be reduced to 0.1 bps/Hz. Orthogonal multiple access performance should be closer to 0.5 bps/Hz by using low spectral sidelobe waveforms such as GMSK. This additional efficiency may be used for example, to allow uplink users of different ACNs or ACN sectors to stay (nearly) orthogonal to one another.

A similar argument can be made for the downlink as well. For example, an ACN downlink carrying 3 Mbps of traffic should be able to contain the transmission spectrum to about 3 MHz, even after coding. Multiple ACNs sharing a single 10 MHz spread spectrum downlink could synchronize downlink frequency hopping so that three downlinks could remain orthogonal.

If more ACNs were added to the constellation controlled spectral overlap could be arranged to minimize interference.

(There are also spatial antenna techniques that can be used to minimize interference which are discussed later.)

E. Anti-Jamming Performance

As a military communication system, the ACN should provide protection from jammers that are inexpensive, easily hidden, nearly undetectable and readily replaceable.

At a minimum, protection should be provided from jammers that can disrupt communication without being detected by routine SIGINT techniques. If a jammer can be detected and located then there is the opportunity to apply active countermeasures, e.g., physical destruction or passive countermeasures, e.g., rerouting.

The main concern is that a jammer on the ground pointed at the ACN will disrupt all uplink transmissions to the aircraft. (Jamming of the downlink to the users is less of a problem, since a ground-based jammer will be within sight of only some of the users, and an airborne jammer can be shot down.)

Significant protection can be provided through the a combination of: spread spectrum signal modulation, the use of secure spreading sequences, i.e., non-repetitive frequency hopping or direct sequence spreading patterns, efficient modulation-coding, and receive antenna discrimination. (Additional protection can be provided at upper protocol layers through adaptive routing, smart error handling and flexible applications.)

The use of secure spread spectrum is a key means of protection and will raise the tolerable jammer to signal ratio at a receiver to:

$$J/S = \frac{(W/R)}{(Eb/No)_{req}}$$

where J= received jammer power, S= received signal power, R= communication data rate, W= spread spectrum bandwidth, and $(Eb/No)_{req}$ is the required energy per bit to noise spectral density. (W/R) is usually referred to as the "processing gain".

Figure V-8 is a plot of the jammer-to-signal power ratio that can be tolerated at a receiver in a well designed spread-spectrum anti-jam system. This ratio is shown as a function of data rate and parameterized by the spread spectrum bandwidth. The values should be considered representative; a specific system design would deviate some from these figures. Since the system is presumed to use secure spread spectrum techniques it can not be disrupted by low power intelligent jammers that could mimic or spoof the communication signals.

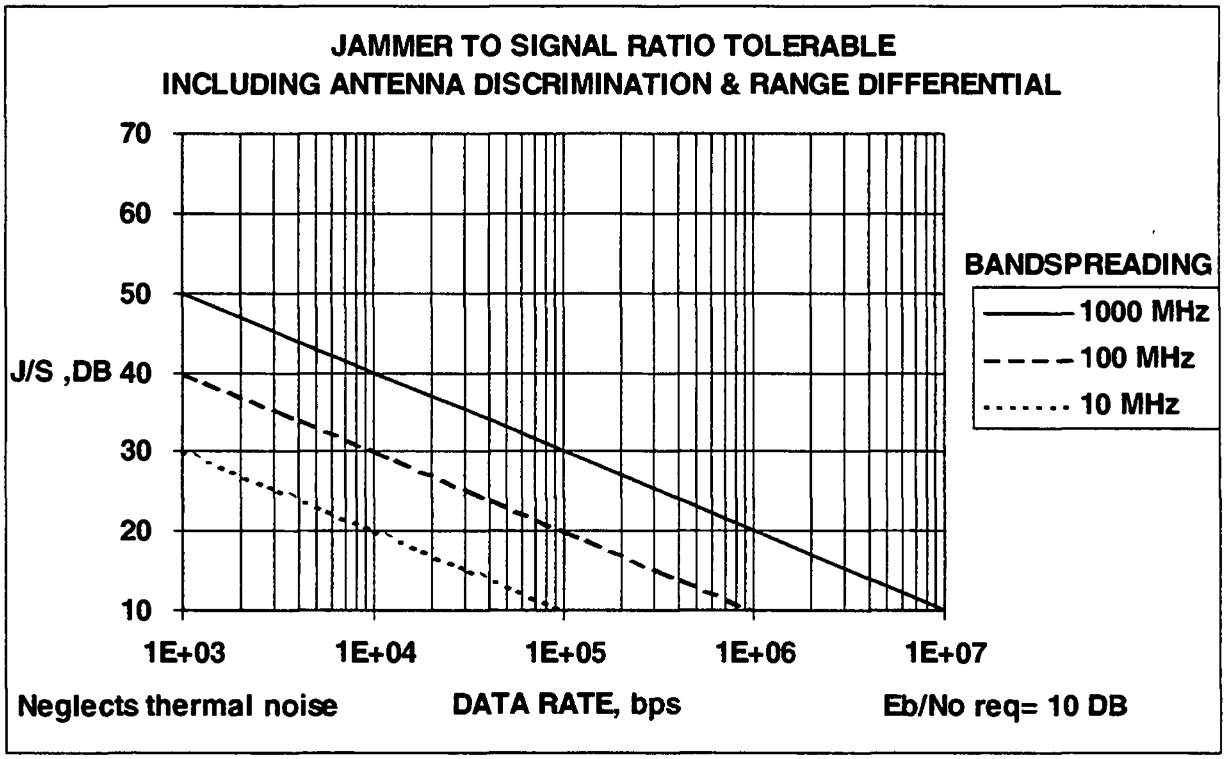


Figure V-8 Anti-Jamming Performance (tolerable J/S shown is at the receiver)

To take an example, suppose the handheld transmitter is low in average power (1 watt), has a omnidirectional antenna (0 dbi gain), and transmits at an average 10 kbps rate. If the transmitted signal is bandspread over a 10 MHz bandwidth, then the jammer must have a transmitted power 100 times that of the user. At an operating frequency of 1 GHz this jammer could be realized as a 4 watt transmitter into a 3 foot diameter dish or 20 watts into a 1 foot diameter dish. Neither of these jammer implementations are difficult for an adversary to achieve.

However, if the antenna system on the ACN is able to discriminate against the jammer by placing a 40 dB null in its receiving pattern in the direction of the jammer, then the jammer must be 10,000 times larger than before. That is, the jammer now requires a 2000 watt transmitter into a 10 foot diameter antenna to be effective. This jammer is certainly going to be easy to locate from its emissions and can then be directly attacked.

Achieving a 40 dB null in an antenna pattern has been demonstrated previously. The issue is to create an adaptable narrow null, so that not many near-by users are also nulled. The ability to achieve a narrow null is determined by the size of the receive array on the ACN; the longer the horizontal dimensions of the array, the narrower the null in azimuth. For instance, a 20 foot long array will produce an null width of about 0.5 degrees at 1 GHz, which translates to about 1 mile in width at a 100 mile range from the ACN. Thus only users that are within a mile or two of the jammer (in azimuth) will be affected. The array need not be "filled" ; a thinned antenna array is sufficient. This is discussed further in the Implementation section.

It should be noted that commercial systems do not provide even the minimal level of jamming protection suggested above. This is true for several technical reasons:

- bandspreading, if used at all, is limited to a fraction of the available spectrum
- short duration repetitive spreading sequences are used for ease in implementation which can easily be spoofed (causing denial of service) or jammed by low power jammers
- effective jammers of commercial systems can have characteristics very similar to users and hence are difficult to discriminate from legitimate users
- receive antenna discrimination is used at base stations to reject broad areas of potential interference, but not to reject strong point sources

F. Low Probability of Detection (LPD) Performance

The ability of an adversary to detect and localize an ACN/HH subscriber would be of concern if this could be accomplished at long range with modest equipment. However, evaluating LPD performance is generally quite complex and is highly dependent on assumptions made about the detector's signal processing sophistication, antenna suite and concept of operations. Complete analysis is beyond the scope of this study.

But as a start in evaluating performance, consider a detector that uses a straightforward combination of a radiometer to measure received energy in the signal bandwidth W over a period of time T following a single beam antenna. An airborne or satellite detection platform is assumed. A signal detection is announce if the total energy received is above a threshold. The "signal-to-noise-ratio" of the decision statistic is well known to be $(T/W)(P/No)^2$ when (as expected) P/NoW <<1, where (P/No) is the signal to noise-spectral-density-ratio at the detectors receiver. This signal-to-noise-ratio will need to be at least 10 dB for a reliable decision. (The exact value required depends on many factors, e.g., number of beam positions being searched, allowed false alarm rate, stability of the platform and nose background, etc.) Figure V-9 shows this signal-to-noise-ratio for the case of a 0.3 Watt transmitter, W= 100 MHz and T= 0.1 sec, which are rather optimistic values from the communicator's point-of-view. 15 dB of additional path loss attenuation over free space to the detector is included. It is seen that the detector would have a detection signal-to-noise ratio greater than 15 dB at ranges less than 100 miles even with a detector aperture of only 2 feet.

While this result is worrisome, it should be noted that the detector's field-of-view with a small aperture is wide (over 30 degrees for a 2 foot aperture at 1 GHz) and is highly likely to include a number of fluctuating sources of RF energy. This would greatly reduce the efficacy of a simple radiometer detector. It also makes localization more difficult. Narrower beams and/or more sophisticated processing would almost certainly be employed.

More sophisticated processing might include a bank of narrower band radiometers, particularly if the communication signal is frequency hopped. Approaches to signal design and their vulnerability to detection is discussed in [Edell]. Lastly it should be noted that if a commercial system were used, a detector can take advantage of numerous predictable signal

features, e.g., known repetitive spreading codes, which would allow detection relatively simply at long ranges.

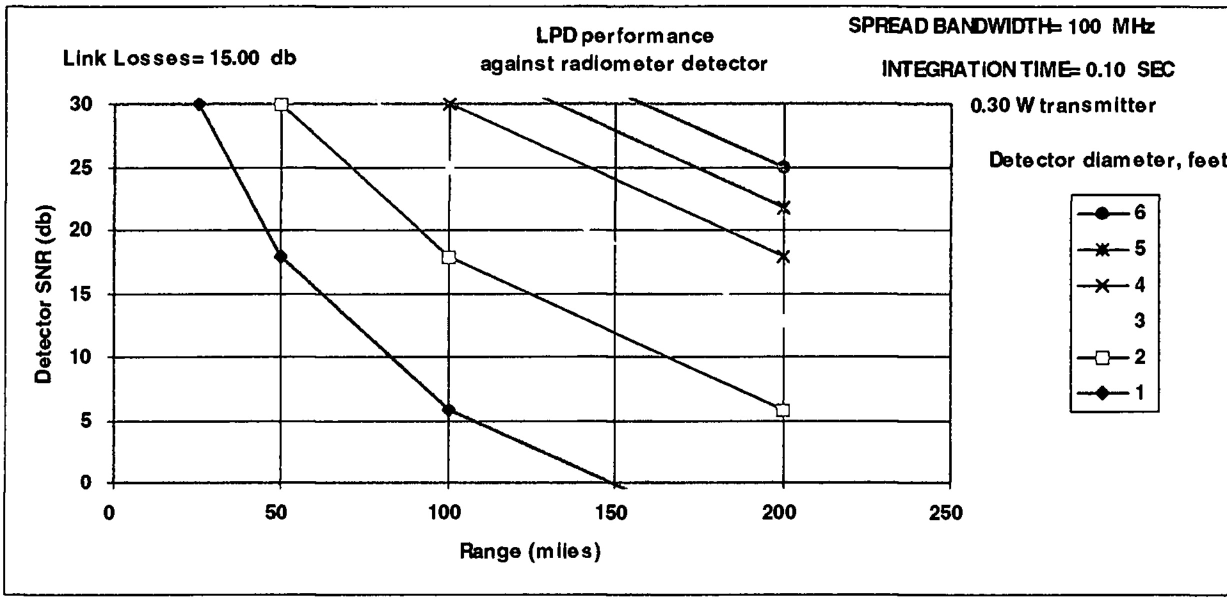


Figure V-9 Radiometer Signal-to-Noise Ratio for a Simple Scenario

G. Spread Spectrum Selection Factors

The use of spread spectrum modulation is recommended for use on both the uplink and downlink. The reasons for this recommendation are compelling and can be summarized by recognizing that spread spectrum can provide:

- protection from frequency-selective propagation degradations over the spreading band caused by multipath
- protection from many forms of electromagnetic interference (EMI) from "friendly emitters"
- protection from jamming
- protection from signal detection
- a technique for frequency reuse

There are two main categories of spread spectrum, frequency hopping and direct sequence spreading. In either case these techniques would be used with robust error control coding. Both techniques can be used to counter frequency-selective propagation losses due to multipath. The anti-jamming performance of both techniques are comparable when spread over the same bandwidth (although direct sequence spreading may be more advantageous by a few dB because it can more easily take advantage of coherent modulation techniques, assuming that a reasonably uninterrupted band of frequencies can be found) Frequency hopping is generally more vulnerable to a determined signal detector. However, on balance of these two main categories of spread spectrum, frequency-hopping is preferred in the ACN environment over direct sequence spreading for two main reasons:

- frequency hopping has the superior ability to work in crowded portions of the frequency spectrum by flexibly adapting its hopping range and selectively avoiding occupied frequencies; direct sequence spreading requires a continuous band of frequencies and is subject to all forms of interference within it unless specialized "excision" techniques are used
- frequency hopping can be used to create orthogonal uplink multiple access channels with relatively weak power control requirements by synchronized hopping; this is much more difficult to do with direct sequence spreading because of its tight synchronization requirements, e.g., about 10 nsec for 10 MHz spreading

(It should also be mentioned that a technique using very short time duration pulse to create an "ultra-wideband" spread spectrum signal is being developed by Time Domain Corp.. However, it is not felt to be practical for use in the ACN handheld system.)

VI. Frequency Selection Factors

One of the most crucial design decisions is the choice of operating frequency. Most desirable would be to find at least 10 MHz of available bandwidth for each of the uplink and downlink. More bandwidth would be even better.

The appropriate range of operating frequencies considered goes from about 225 MHz to about 2 GHz. There is not enough bandwidth available below 225 MHz to practically consider. Above about 2 GHz propagation factors are too limiting for the system concept using relatively simple antennas. (However the door could be left open to consider systems operating at higher frequencies using highly directive multibeam ACN antennas.)

Both technical and allocation factors must be considered. Indeed, it is almost certainly the case that technical factors will only limit the range to be considered whereas allocation factors will dominate the specific choice of frequencies.

A. Technical Factors

A summary of technical factors are.

Favoring the use of lower frequencies:

- less free-space propagation path loss allows use of low gain antennas
- simple ACN antenna (blade) may be sufficient to close link
- less foliage attenuation

Favoring the use of higher frequencies:

- for the same ACN antenna pattern, antenna arrays are smaller which permits shaped pattern, sectored coverage, higher gain beams, nulling pattern for anti-jam
- smaller, more efficient antennas on handset
- allows the possibility of moderately directive antenna for the handset

B. Allocation Factors

The allocation factors were examined by the Joint Spectrum Center and are presented in [JSC]. The bands that were examined were:

- Government - mobile, military
  335.4 - 399.9 MHz
  1350 - 1390 MHz
  1435 - 1525 MHz
  1755 - 1850 MHz
- Government - mobile, non-military
  406.1 - 420 MHz
- Government - other services
  420 - 450 MHz: radiolocation
  902 - 928 MHz: radiolocation

- Non-government bands
  450 - 806 MHz
  806 - 902 MHz
  1850 - 1990 MHz

C. Conclusions

As a result of the evaluation of the frequency band issues the following bands are the most desirable and likely for operation:

- 335.4 - 399.9 MHz
- 1350 - 1390 MHz
- 1755 - 1850 MHz

However it should also be concluded that the ACN handheld system will need to be frequency agile for worldwide utility.

VII. Implementation

The study concentrated on system level design and did not delve deeply into specific implementations . In this section three of the high-leverage implementation areas are discussed in order to provide a comfortable feeling that the recommended design approach is feasible. Implementation is a key area that needs additional detailed examination.

A. Antennas

The antenna selection is an important aspect of the overall system design. Clearly the quality of the link and the resulting impact on the performance of the communication system are highly dependent on the choice of antenna, both on the ACN and on the handset.

This section begins with a discussion of three classes of antennas for the ACN. Next two potential antennas for the handset are examined. In both of these cases the main trade-off is higher gain at the cost of a larger, more complex antenna versus lower gain using a smaller, simpler antenna. All of antennas considered have merit for different scenarios. Perhaps the ultimate solution is to design a system capable of accommodating several antenna types, either interchangeably or simultaneously, and let the terrain, desired communication modes, and other appropriate factors of the deployment guide the selection of antenna. Next is a short discussion of the impact of polarization of the antennas, i.e., linearly versus circularly polarized antennas. The section concludes with a discussion of other system factors that affect the selection of the antennas. These other factors include the choice of operating frequency, system bandwidth, and frequency division versus time division multiplexing of the up and down links.

1. ACN Antenna Considerations

There are several primary features that are required from the ACN antenna. Foremost is that there is enough gain over the coverage area (actually EIRP and G/T) that a link with adequate margin can be established with the desired data rate. This means that the antenna on the ACN must have more gain toward the horizon to overcome the longer propagation distance as well as increased chance for attenuation and blockage for users at the edge of coverage. A simple example using rounded numbers illustrates the point. The ACN will fly at roughly 12 miles and the desired coverage area is 100 miles in radius. Thus the distance from the ACN to users will vary from roughly 12 miles to 100 miles. Since it is desirable that the signal strength received (or the quality of the link) be independent of location, the antenna on the ACN should compensate for the varying distance to the users. This is accomplished readily by designing an antenna that has roughly 20 dB more gain toward the horizon (edge of coverage) than in the direction directly below the ACN.

The second primary feature of the ACN antenna is that it assist in providing anti-jam (AJ) capability for the system. The two methods for providing AJ capability are broad system bandwidth to allow a spread spectrum signal and antenna nulling to reduce the signal strength of the jammer in the receiver electronics. The third primary feature is the antenna must function in the highly difficult EMI environment of the ACN. Unlike the legacy systems, the handheld

system is being designed knowing it must co-exist with the larger number of other communication systems on board the ACN. Thus all aspects of the design, including the frequency and antenna selections, should be chosen considering the impact on co-site interference.

Three types of antennas are considered in this section. The most likely locations for the ACN antennas are in the SAR pod on the belly of the fuselage, the exterior surfaces of the tail wings, and the sides of the fuselage. The antennas considered range from simple wire antennas which may have adequate albeit limited performance to a multibeam antenna that is probably best implemented as a digitally beam formed array. (However, a relatively small array.) This antenna would offer many performance enhancements for the ACN. The analysis performed in this study is detailed enough to gauge the differences among the antenna designs and to assess the approximate performance, but they should be considered as only the starting point for an actual design. The results presented are theoretical directivities for simplified geometries of the antennas that would be placed on the ACN. The calculations assume perfect conductors, lossless dielectrics, and, in the first two configurations, an infinite ground plane to simulate the affect of the ACN surface. The technique used to synthesize the antenna patterns in the third configuration is relatively unsophisticated, but it does indicate the kind of performance capable from a beamformed array.

a) Simple Wire Antennas

One of the simplest antennas, which could be considered for the ACN, is a blade or monopole antenna. This antenna belongs to the class of antennas known as wire antennas. While physically they are more complicated than a simple wire, analytically they are modeled as a thin cylindrical conductor. The monopole antenna has many attractive features. It is compact; it has an azimuth-symmetric pattern, and it provides more gain to the horizon. The monopole has a theoretical directivity of 2.3 dBi to the horizon, and a physical realization of the antenna would have gain on the order of 0 to 1 dBi. Unfortunately this is not enough gain to establish links at the desired range and data rates with acceptable transmitter power. Section V-A above showed that the required antenna gain is a function of frequency of operation. In the UHF region, 225 to 400 MHz, an antenna with gain of 5 to 8 dBi is desired. At higher operating frequencies, 0.8 to 1.8 GHz, an antenna with gain of 10 dBi or more is desired.

It is possible to use other wire antennas that are still attractive for their simplicity and physical size, but having higher gain. Two configurations are considered here. The first is a half-wave dipole placed $\lambda/8$ below a ground plane, and the second is an array of two co-linear dipoles again placed $\lambda/8$ below a ground plane and separated by 0.6λ. Physically the ground plane would be the belly of the fuselage of the ACN. The patterns are calculated using image theory. The directivities are calculated by finding total radiated power through integrating the pattern over all space. The power patterns for these two antennas along with the monopole pattern are shown in Figure VII-1. The calculated maximum directivities for these antennas (toward the horizon) are monopole = 2.1 dBi, single dipole above ground plane = 6.8 dBi, and two co-linear dipoles above a ground plane = 9.1 dBi. A uniformly excited array of two co-linear dipoles has two nulls in the antenna pattern as the observation point is scanned from the

horizon to nadir. Since nulls are undesirable in the antenna pattern the array has been excited with three signals which synthesize a broadside beam plus one beam each to fill in the two nulls.

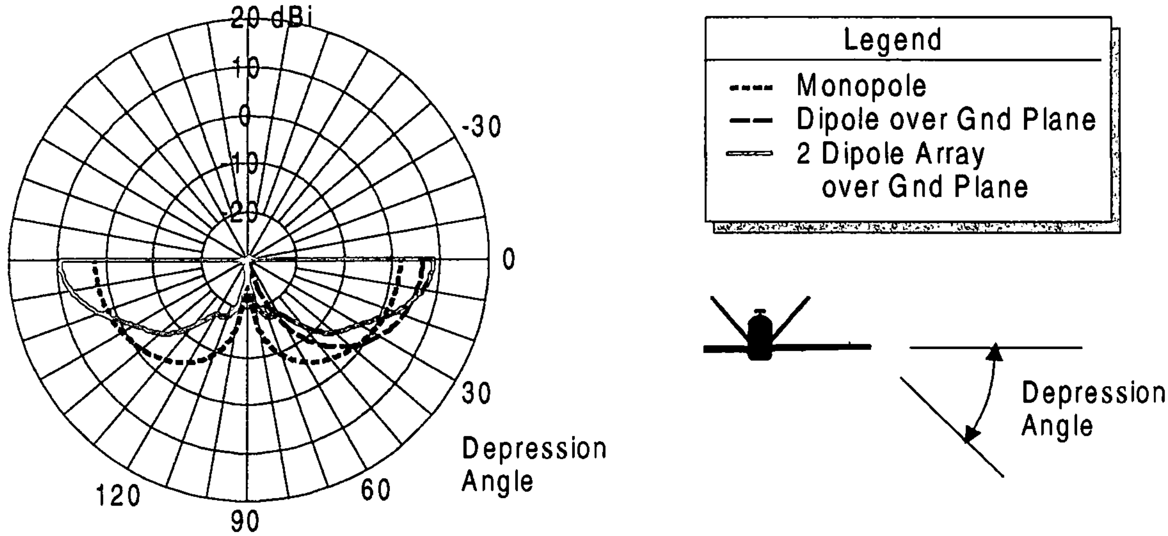


Figure VII-1 Calculated field patterns of simple wire antennas considered for the ACN.

Several observations can be made from the antenna patterns. Clearly the monopole antenna does not have enough gain, especially if the system operates at frequencies above 1 GHz. The half-wave dipole and the co-linear array have gains that are approaching that desired from the link calculation. These are relatively simple antennas and have patterns that are azimuthly symmetric. Thus one of these antennas might be useful in a proof of concept demonstration or early fielded system investigations. The theoretical null at nadir (along the axis of the dipole) would not be infinitely deep as shown in the plot. In a fielded system scattering from objects on the ACN or in the local vicinity of the users would tend to fill in the null. The actual depth of the null, however, would have to be determined through measurement or more sophisticated analysis.

b) Simple Sectored Patch Antenna Array

The next level of sophistication is a simple sectored antenna. One possible realization uses a two-element array of patch antennas for each sector as shown in Figure VII-2. There are four sectors, one on each of the faces of a four-sided pyramid. In the pattern calculations that follow, the face of the pyramid is at a 30° angle toward nadir (with respect to the horizon). Standard formulations are used which treat the patch antenna as a combination of two radiating slots. The plots are for the total power, i.e., contain both the Eθ and Eϕ components. Again the belly of the fuselage is treated as an infinite ground plane, and the antennas in the array are imaged in the ground plane.

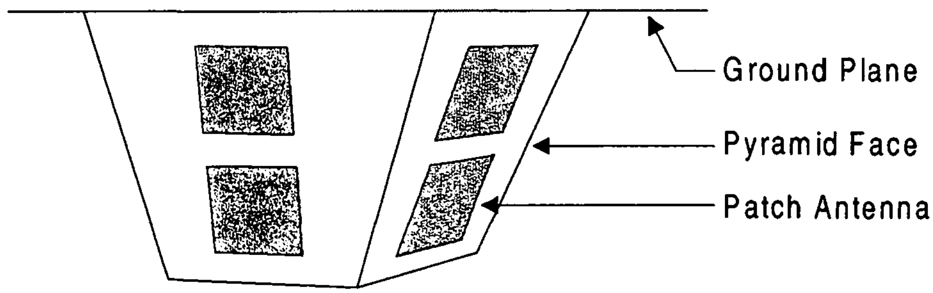


Figure VII-2 Illustration of the four-sided pyramid containing two-element patch antenna arrays.

The calculated antenna patterns for one sector (or one face of the array) are shown in Figure VII-3. In the figure there are plots of the pattern in four different azimuth planes. Azimuth angle of 0°corresponds to the plane perpendicular to the face of the array as shown at the bottom of the figure. The nominal coverage area of each sector is ± 45°. Thus azimuth planes of 0°, 22.5°, and 45° are shown. The azimuth plane of 90° is also shown to check the spillover into the sector on the opposite face of the pyramid. The patterns are given as a function of depression angle. Since the face of the pyramid is placed on a 30° tilt with respect to horizontal, the nominal pattern (without beam steering) peaks at a depression angle of 30°. The patterns in the figure have been calculated using beam steering to produce plots that have the peak of the beam closer to the horizon. The ability to create a well defined beam peak is limited since the array only contains two elements, but these results do show that limited depression angle scanning is possible.

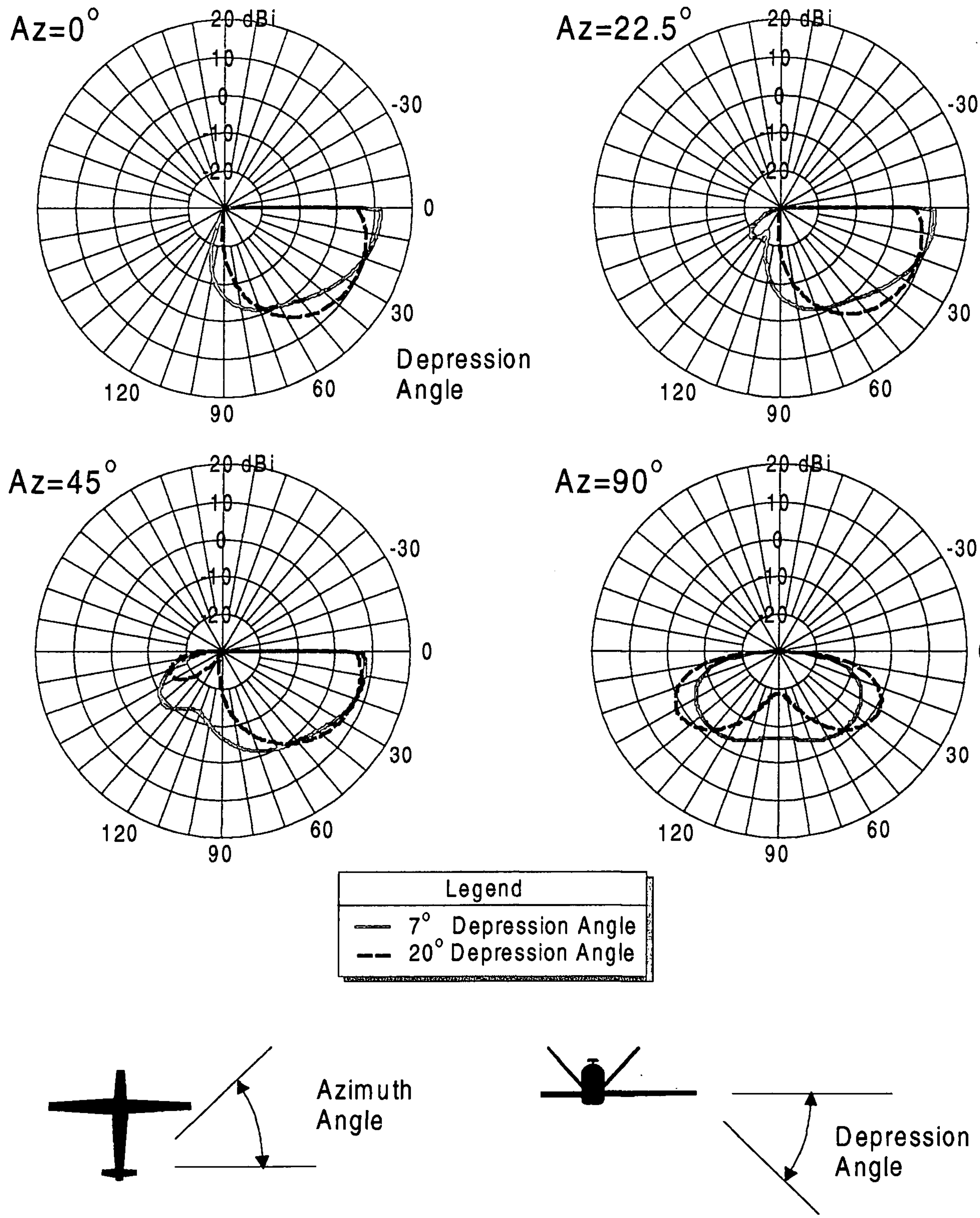


Figure VII-3 Antenna patterns for the simple sectored patch antenna array.

There are several advantages of this antenna over the previous wire antennas. The sectored coverage provides a pattern with several dB higher gain since the energy is not uniformly distributed in azimuth. The peak gain is about 10 dBi over the full sector, which is the

nominal value desired from the link calculations. The sectored coverage also provides some degree of AJ capability since the sector in which the jammer is located can be either turned off or the antennas can be phased to place a null on the jammer. In the last case the antenna pattern would be significantly distorted over the entire sector, but it offers the possibility that some users could still establish a link. Another advantage of sectoring is that it allows the possibility of frequency reuse. Finally, the sectored coverage and the use of at least two elements allows the possibility to electronically scan the beam to reduce the distortion in the coverage area caused by the aircraft banking while loitering on-station. Compensation for banking becomes more important as the antenna pattern is more highly shaped to increase the range and availability of service at the edge of coverage. In Figure VII-3 the two antenna patterns shown represent the nominal antenna pattern and one pattern to compensate for aircraft banking. The curve that peaks at a 7° depression angle is the nominal pattern. This would be used in the fore and aft sectors and on the side sectors if the aircraft was not banking. The 20° depression angle pattern would be used, say, in the right sector if the aircraft was banking to the left.

c) Multibeam Patch Antenna Array

The third antenna is the most sophisticated of the three, but adds many useful features. It is a patch antenna array located on the tail wing of the aircraft. This is an ideal location for an antenna for the handheld system. Its inclination (43° from vertical) makes it well suited for forming beams with appreciable gain from the horizon to nadir, and physically it is relatively large so a variety of useful patterns can be synthesized. The nominal size of the array considered here is three elements wide by sixteen elements tall with half-wavelength spacing. At an operating frequency of 1 GHz where the wavelength is approximately one foot, the size of the array is about 1.5 feet by 8 feet. This should fit on the tail wing that is approximately eleven feet tall, five feet wide at the base and 2.5 feet tall at the top.

The nominal pattern for the array is shown in Figure VII-4. The pattern roughly follows a $\csc^2$ dependence as a function of depression angle. In the mathematical model of the propagation, the $\csc^2$ dependence exactly compensates for the free space propagation loss factor so that all users on the ground receive the same signal strength from the transmitter regardless of distance from the ACN. The patterns shown are synthesized using the Woodward technique [Jasik]. The plot shows a sequence of three patterns steered to peak at different elevation angles to compensate for the aircraft roll as the ACN loiters on station. Again the 7° depression angle is the nominal pattern. The antenna pattern that peaks at a 14° depression angle would be used for the right sector as the aircraft banks to the left, and the pattern that peaks at a 0° depression angle would be used for the right sector as the aircraft banks to the right. Note the shape of the pattern and the ability to fine-tune the peak directivity is much greater in the array with a relatively large number of elements compared to the two-element array. In these plots only one column of the array is excited so that the beamwidth will remain large enough to fill a sector.

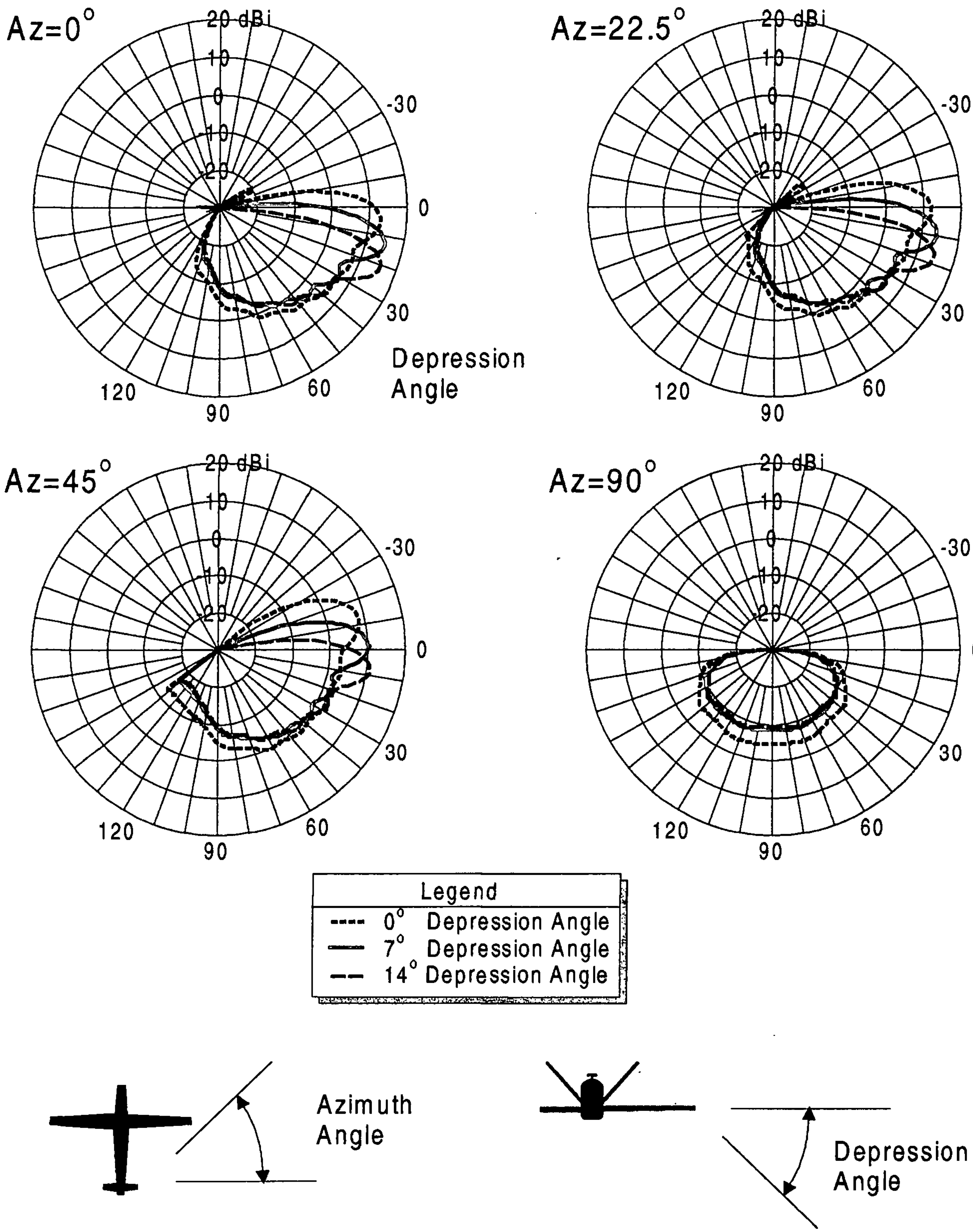


Figure VII-4 Cosecant squared pattern from a 1-by-16 patch antenna array located on the tail of the ACN.

While the ability to form a more accurate representation of the csc^2 shape and the ability to better position the peak of the beam are clearly shown with the array, that alone is probably not justification for constructing the more complex array. The real power of the array is in the ability to form multiple simultaneous beams with a variety of antenna patterns and thus offer better communication services for the users. Several examples of other useful antenna patterns are listed here. The first example preserves the csc^2 pattern shown in Figure VII-4 but has a narrower beamwidth in azimuth. This is readily accomplished by using two or three of the columns in the array rather the just one as stated above. These narrower sectors can be steered off boresight to allow the formation of two or three csc^2 beams from the array rather than just one. This would aid in a frequency reuse scheme and would provide additional AJ capability. A detailed example of increased sectoring using an array on the side of the fuselage is given below. A second example is a pattern that performs adaptive nulling in response to jammers. This provides even more AJ capability while minimizing the perturbation to the rest of the coverage area. This topic is also covered in more detail below. The final example is to form spot beams that could serve high data rate or disadvantaged users, i.e. a group of users in a heavy foliage fade or in a localized urban setting where multipath and building attenuation will decrease the signal strength. An example of a spot beam is shown in Figure VII-5. Note that the peak directivity of the beam is 22 dBi. This is an increase of at least 12 dB over the directivity of the nominal pattern in the same direction.

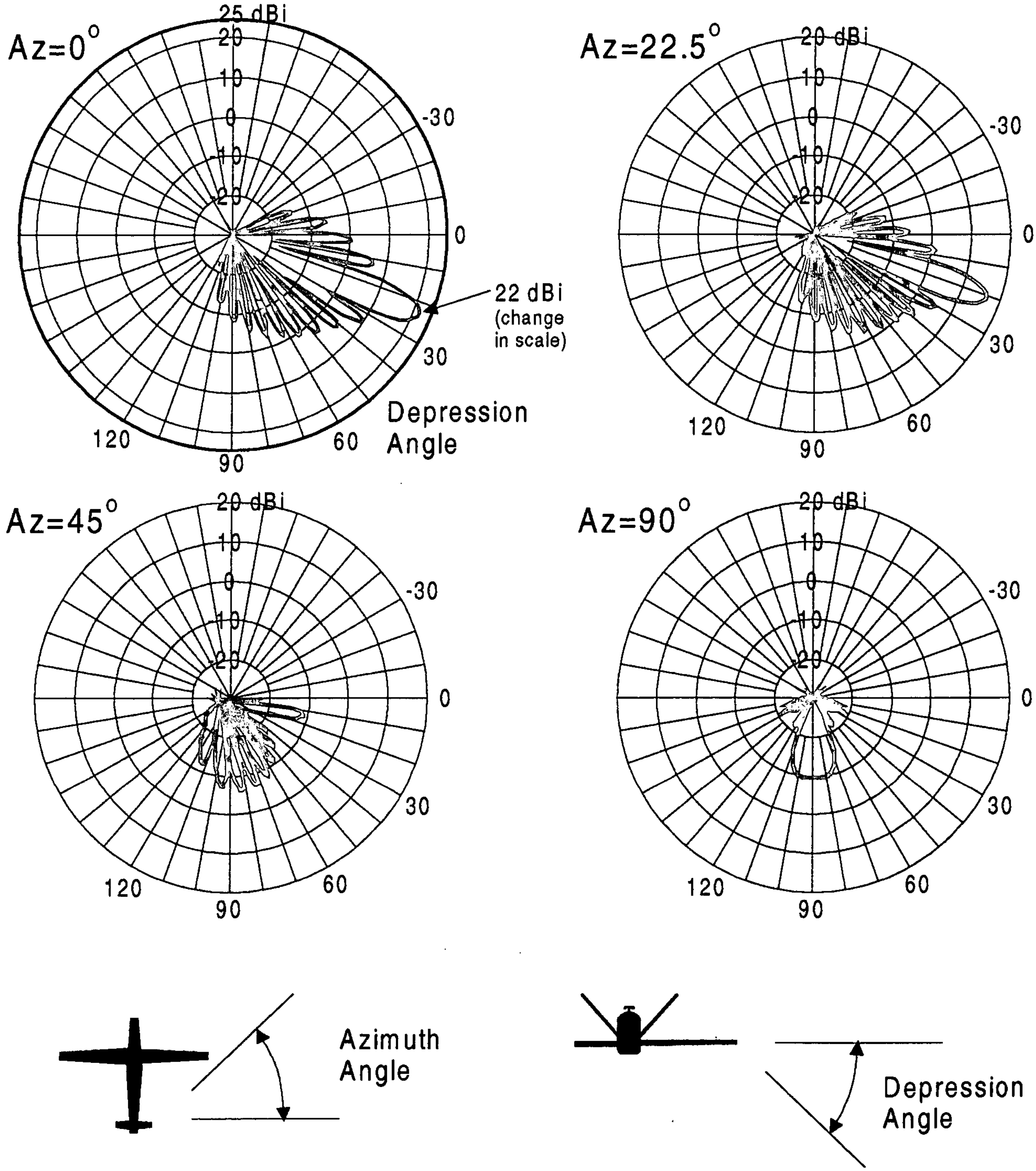


Figure VII-5 An example of spot beam pattern steered to 0° in azimuth and 23° in depression angle

Another possible location for a phased array antenna is on the side of the fuselage. An array of approximately the same size could be located either in front of or behind the wing. This location provides more horizontal aperture, which aids in forming multiple sectors toward the side of the ACN. Figure VII-6 shows antenna patterns that provide coverage to four 30° sectors.

This array is five elements high by sixteen elements wide. The face of the array is at a 10° depression angle. The elevation cuts at constant azimuth angle are shown on the left side of the figure. Note that reasonably good elevation shaping is obtained with only five vertical elements. Azimuth cuts at constant depression angle are shown on the right side of the figure. The pattern shows four well-defined sectors. The patterns were synthesized using the Woodward technique.

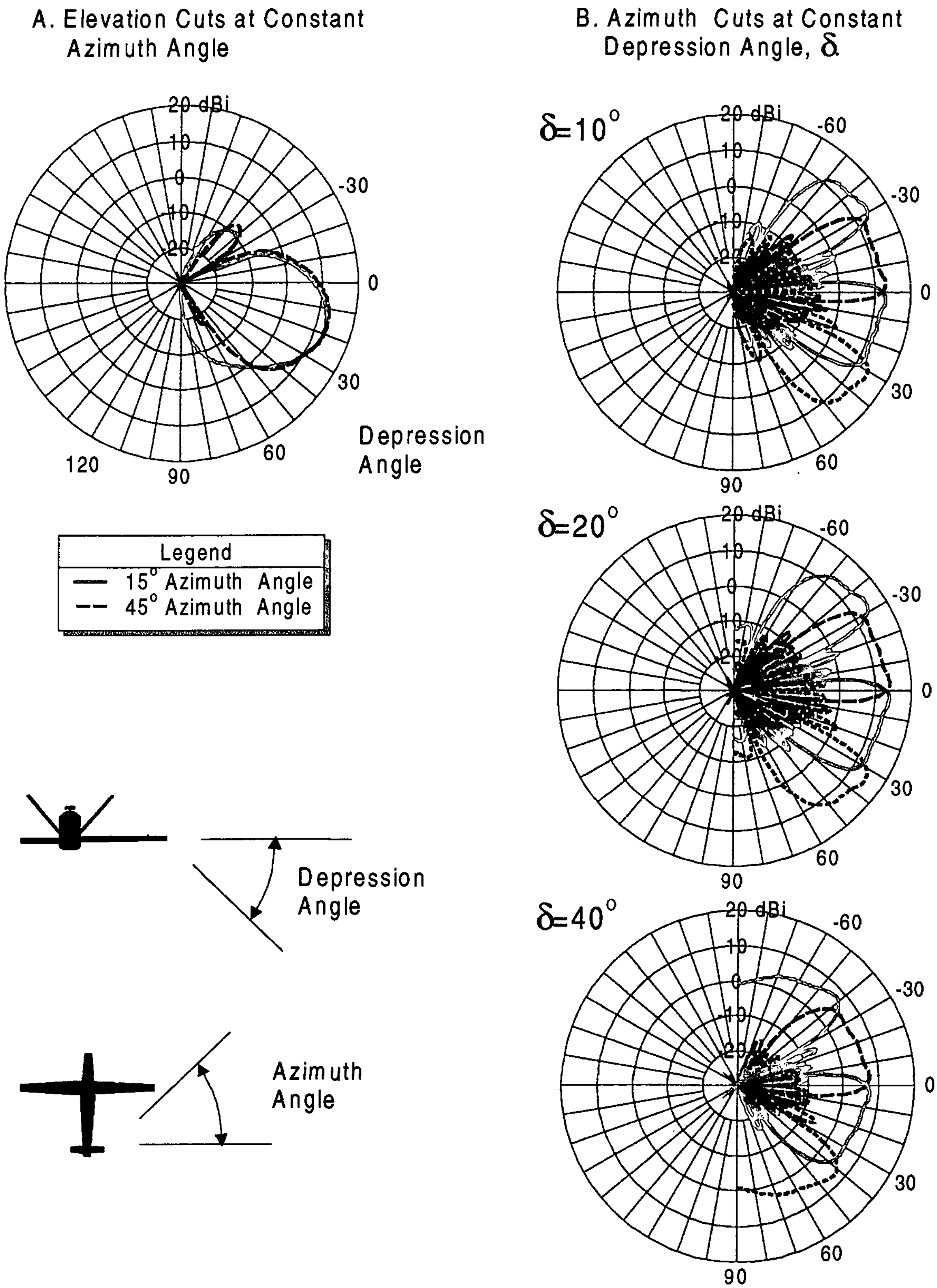


Figure VII-6 Antenna patterns for a 16-by-5 element patch antenna array located on the side of the ACN fuselage. The patterns are designed to cover four 30° sectors off the side of the ACN.

There are many system strategies for using a multibeam, digitally beamformed antenna. Perhaps the ultimate strategy is to place an individual spot beam on each user. However, the required electronics and electrical power may be excessive for the ACN. A more realistic scenario is to have a limited number of beams, perhaps ten or so, that can be formed via digital beam forming. At least one csc^2 pattern is reserved for links to request initiation of service and for general uplink service. This pattern could form a null in the presence of a jammer and still allow an appreciable portion of the users in the sector to communicate. The other beams could be used to form spot beams for high data rate links or pockets of disadvantaged users as described above.

Another interesting possibility for digital beamforming is implement a maximal ratio combining instead of a traditional phased array. The maximal ratio combining approach is another technique that can be explored toward the goal of establishing the most robust link. Maximal ratio combining is similar to a conventional beamforming in that there are many antenna elements and the signals received by each element are combined to form a stronger signal then the single element receives alone. In the conventional approach the signals are combined to steer the main beam in a particular direction, whereas in maximal ratio combining, the signals are combined to form the maximum received signal without regard to shape of the antenna pattern. The reason this technique has merit is the multipath environment inherent in terrestrial wireless communication and the possibility of blockage by portions of the aircraft. Multipath causes dramatic signal variations (10 dB or more) over distances of less than a wavelength and blockage from, say, the wing can be even more drastic. Since the antenna array is larger than one wavelength, this leads to the possibility of combining the received signal from each element in other ways than simply pointing a beam in a particular direction.

There is a disadvantage of this antenna besides the increased complexity of construction. The location of the array on the tail wings or on the side of the fuselage provides excellent coverage to the sectors on either side of the ACN but not for the fore and aft sectors. Thus the enhanced performance made possible from these arrays would not be available continuously as the ACN's orientation is changing while it loiters on station. Some strategies for providing the same level of performance in the fore sector include placing an array in the nose where the EO sensors are currently located or along the leading edge of the wings. For coverage in the aft sector, one could explore using the skid plate located on the bottom of the tail section. This may provide adequate vertical aperture for high gain toward the horizon, especially if the antenna could be deployed several feet when the ACN is on station. More detail on the ACN's physical structure is needed before detailed analysis is possible.

d) Antenna Nulling

It is desirable for the receive antenna to aid in the AJ capability of the system by providing antenna nulling in the presence of jammers. Perhaps the simplest approach to nulling is through the use of a sectored antenna and simply turn off the sector(s) affected by the jammer. Unfortunately this approach would likely deny service to a large number of users making the jammer successful unless the sectors are relatively small.

A more desirable approach is to use a fully controlled phased array that allows for weighting the received signal at every element. This is possible in a digitally beam formed array. With such an antenna array, adaptive array processing techniques can be used to synthesize antenna patterns to null several jammers simultaneously. One of the most important parameters in synthesizing an antenna pattern with a null is the angular width of the null since this indicates how many users will be denied service. The size of the antenna array for the most part determines the minimum size of the null width. Larger arrays have the ability to produce smaller null widths. In addition to the size of the array, the null width is dependent on the synthesis procedure and the coordinates of the jammer with respect to the antenna. An accepted rule of thumb, however, is that the minimum null width, defined at 10 dB down from the nominal pattern, is 1/3 the half-power beamwidth of the antenna. Assuming an antenna array with size of 8λ-by -2λ, the minimum null width is around 2° to 3°. (At 1 GHz operating frequency this array is about 8'-by-2' which would fit on the tail wing or on the side of the fuselage in front of or behind the wing.) A larger antenna array may be possible, but it requires a detailed study of the Global Hawk.

An example of an antenna pattern containing two sectors each with one null is shown in Figure VII-7. This is for the antenna array mounted on the side of the fuselage as described above, but the general results are equally valid for the antenna array mounted on the tail. A modified Woodward synthesis technique was used to create the pattern. This technique is relatively unsophisticated, but it serves to illustrate the point. The resulting null width is over ½ the half-power beamwidth. In an actual system more sophisticated adaptive array processing techniques would be used.

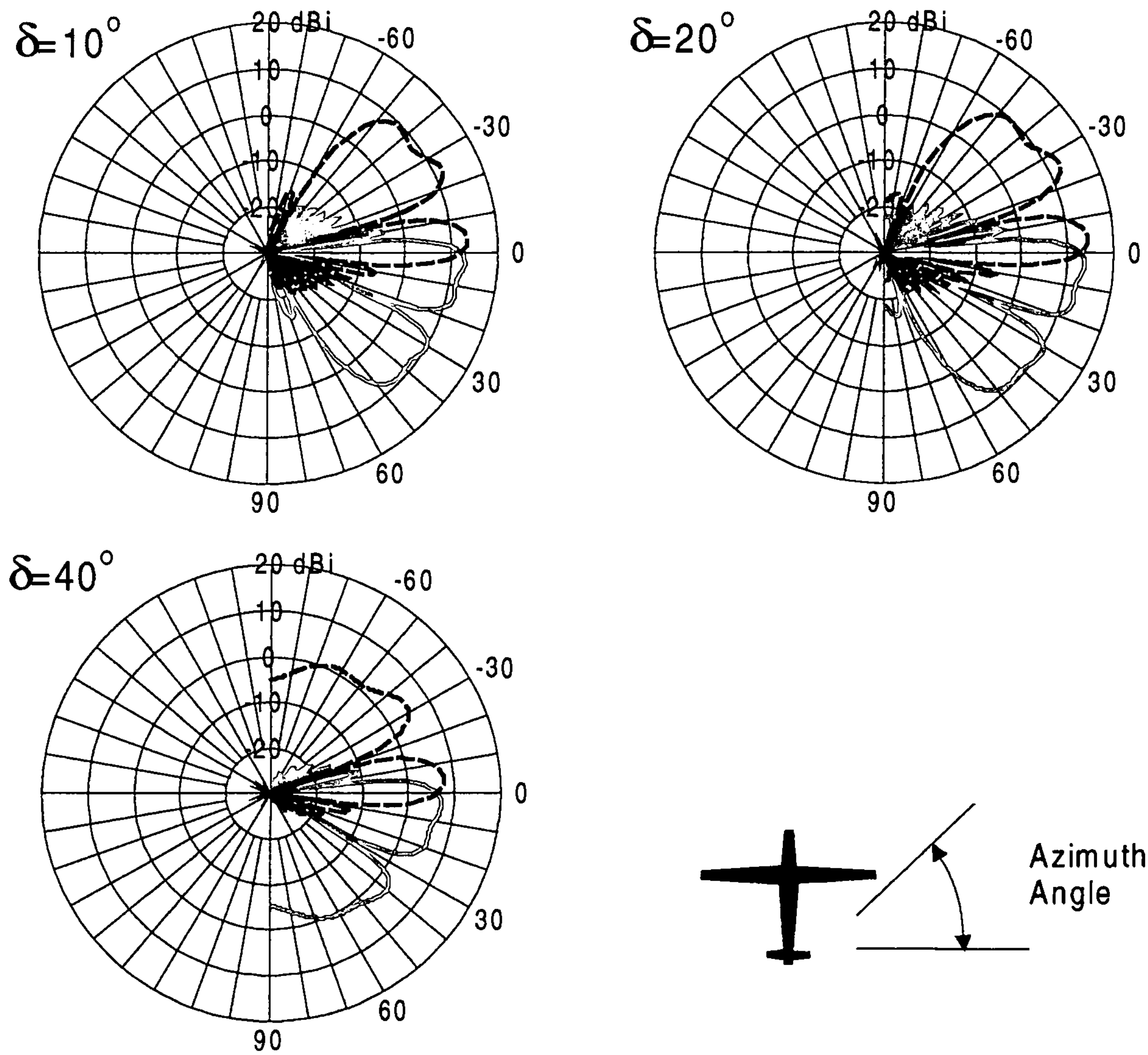


Figure VII-7 An example of an antenna pattern containing two sectors each with one null. Only azimuth cuts at a constant depression angle are shown. The elevation cut is similar to that shown in Figure VII-6.

2. Handset Antenna Considerations

The desired characteristics of the handset antenna are that it requires no or very little setup and maintenance, that it performs well for users on the move, and that it is inexpensive. An ideal antenna for these requirements is a monopole antenna (or a similarly performing variant such as a loaded dipole). These are in wide spread use for cellular telephony and have proven their utility. The pattern for these antennas are azimuthally symmetric and, thus, are reasonably independent of orientation. The only disadvantage of this antenna is its relatively low directivity of about 1-2 dBi. However, the low gain is a consequence of the near omnidirectional pattern, so it is accepted in the trade-off to obtain an easy to use and inexpensive antenna.

There is another antenna that may be considered for users requiring higher data rates or are likely to be on the edge of the coverage area. This is a simple four element electronically scanned array. It is possible to achieve over 10 dBi of directivity in a scan cone of 45° from bore sight with this antenna. The extra 10 dB of directivity could be significant for many users especially if the antenna can be inexpensively manufactured and is easy to use. It is possible that the antenna can be inexpensive if it is given a minimum amount of functionality. Physically the antenna would be two-elements by two-elements spaced just over one-half wavelength. At 1 GHz operating frequency the antenna would be about 1 ft. by 1 ft. by 0.25 inch thick. Electrically, the antenna could switch between a small number of different beams rather than continuously scan as in larger phased arrays. This is possible because the beamwidth is relatively large. Figure VII-8 shows two patterns from the antenna. Figure VII-8a shows the beam switched to give a maximum on boresight, and Figure VII-8b shows the beam switched to give a maximum at 20° or so from boresight. Note that the pattern gives 10 dBi of directivity out to about 40°. Since only five beams are needed to cover the scan cone, the phase shifter at each element only needs to have three states. This relatively simple phase shifter could be constructed in the same printed circuit board as the patch antennas and the small number of diode switches to control the phase shifter could be easily attached using modern circuit board fabrication techniques.

An antenna like this could find use for vehicle mounted applications where several of these antennas are placed on the vehicle. This antenna could also be useful for dismounted users since the antenna itself can be made to weigh on the order of 1-2 pounds, and a simple signal strength meter could be included in the handset to aid in the initial pointing of the antenna. An even smaller directional antenna is possible by using a single patch. This antenna would be approximately 6 to 8 inches on a side (1 GHz operating frequency) and weigh approximately 1 pound. The directivity of this antenna, however, would only be 5-6 dBi instead of the 10 dBi achieved with the four-element array.

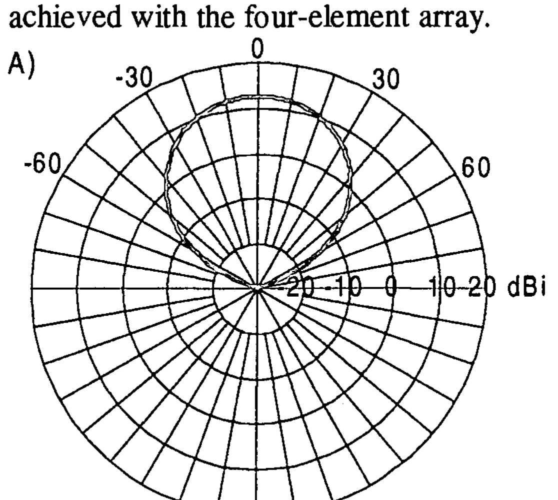


Figure VII-8 Antenna patterns for a four-element (2-by-2) patch antenna array for enhanced handset performance. The pattern can be electronically scanned to maintain 10 dBi directivity within a 40° cone.

3. Antenna Polarization

The polarization of the electromagnetic waves relative to the antenna is an important aspect of the system design. Having the receiving antenna incorrectly aligned to the incident field can lead to little or no reception of the signal even though the signal levels are adequate in the vicinity of the user. Typically communication systems are designed with one of two types of polarization, either linear or circular. The basic characteristic of linear polarization is the orientation of the electric field component of the wave. Most cellar telephone systems are designed with vertical linear polarization. The evidence for this is the vertical orientation of the dipole antennas used on the base station towers. For maximum reception the user should orient the handset so the dipole antenna is also vertical. In the absence of scattering and multipath, the user will receive little or no signal if the dipole antenna on the handset is oriented horizontally.

Circularly polarized waves are characterized by having the electric field component rotate as the wave propagates. The field can rotate in either a right-hand or left-hand sense giving rise to the designation of right-handed or left-handed circular polarization. The advantage of circular polarization is that the receiving antenna is more forgiving in regard to its orientation with respect to the incident signal. Many satellite communication systems are circularly polarized for this reason. The space segment of mobile satellite service systems currently under development: Iridium, Globalstar, and Odyssey, are circularly polarized.

The ACN has attributes of both a terrestrial cellular system and a satellite system, and thus it is not obvious which type of polarization is most appropriate. The majority of the users will have fairly low observation angles to the ACN. This makes vertical linear polarization a likely candidate since most users will know the basic geometry between the antennas. The issue becomes a little cloudy if a patch antenna array is used on ACN (either the pyramid or the larger array on the tail). These antennas will not have pure vertical polarization like the wire antennas described above. With the patch antennas on the ACN, the user should be able to reorient the handset if the signal level is dropping because of polarization mismatch. However, the user may also have to reorient the position of the handset because it is in a local fade caused by ground bounce or some other strong multipath object. Thus the polarization issue is adding another factor in the local fading environment at the handset.

A hybrid polarization scheme is another candidate that warrants consideration. For example, a linearly polarized antenna will receive half of the signal strength contained in a circularly polarized wave regardless of orientation (as long as the antenna is in the plane normal to the propagation direction) and regardless of the sense of circular polarization. Accepting a 3 dB loss in the maximum received signal may enable a less severe local fade environment at the handset. In this hybrid scheme a linearly polarized dipole antenna will be used on the handset and circularly polarized patch antennas would be used on the ACN. If the small patch array was use at the handset as described above, it could be circularly polarized and not incur the 3 dB loss. Thus the maximum data rate could still be achieved for users who desire it and are willing to use a directional antenna to achieve it.

A more detailed study of the polarization implication should be included in design of the antennas for the ACN. This can take place once the basic type of antenna for the ACN is decided, i.e., simple wire antenna, sectored patch antenna, or multibeam patch array. This study

should also include the other contributors to the local fade environment at the handset and may need to be supported with measurements since the geometry of the link from the ACN to handset is different from that in cellular telephony and is not well documented.

4. Other System Issues Impacting Antenna Design

The desired antenna pattern is certainly a major factor in the antenna the design; however, it is not the only one. Other important factors include the choice of operating frequency, system bandwidth, degree of AJ robustness, and frequency division versus time division duplexing of the up and down links.

The choice of operating frequency is complex, involving many factors both technical and political. The dominant technical aspect is the degree of propagation losses and the effects of blockage as functions of frequency. A lower operating frequency has less free space propagation loss than higher frequencies. Thus, assuming antenna gain of zero dBi on the handset and approximately 10 dBi on the ACN, higher data rates are possible at lower frequencies. Another factor favoring lower operating frequency is lower foliage attenuation. Technical factors favoring higher operating frequencies include more precise antenna pattern shaping and wider system bandwidths. Both of these factors benefit AJ robustness and more sophisticated system operation like frequency reuse and multibeam antennas. However, the overriding issue in deciding the operating frequency is likely to be political/administrative. Frequency bands in which military systems can operate are allocated by national and international agencies for use in the US and globally, respectively. Even within a theater of operation, the frequency use is allocated by military agencies so that the multitude of communication and radar systems has the best chance to operate properly.

The choice of operating frequency will impact the type of antenna selected on the ACN. Lower frequency will favor simple azimuth-symmetric antennas such as blades and simple dipoles while higher frequencies will favor antenna arrays most likely composed from patch antennas. A higher operating frequency also opens the possibility for simple arrays at the handset.

The overall system bandwidth will also impact the choice of antenna. Relatively simple dipole and patch antennas can accommodate system bandwidths on the order of 20%. It may be possible to extend the bandwidth to 30% or so with slightly more complex dipoles or patches. However bandwidths greater than this will require retuning some aspect of the dipole or patch antenna or using a broadband radiating element.

The last system issue impacting the antenna design discussed here is the choice of frequency division or time division duplexing for the up and down links. The trade-off considered here is the impact on the antenna, transmitter, and receiver electronics rather than the impact on the communication system. The basic trade-off involves the instantaneous data rate (or burst rate) versus the complexity of the electronics.

A frequency division duplexing system uses two different frequencies for the up and down links. The advantage of this system is that the links can be used simultaneously (full

duplex) to increase the data flow. However, the electronics must be more complex to accommodate the full duplex system, namely the transmitted signal must be prevented from entering the receiver with too much signal strength to disrupt the reception and processing of the desired signals. There are two strategies to minimize the leakage of the transmit signal into the receiver. The first uses two separate antennas, one for the transmitter and one for the receiver. Physically separating the antenna reduces the leakage by several tens of decibels so that, hopefully, simple filters can enable the system. If not, more complex filters or active cancellation of the leakage signal can be used. The second strategy involves using a single antenna with a diplexer or circulator to keep the signals in either the transmitter and receiver electronics. Normally the diplexer or circulators does not provide as much isolation against the leakage as separate antennas, but it is useful in some applications. Typically a handset which does not have a strong transmitter can use the single antenna schemes since not as much isolation is need to keep the absolute level of the leakage signal below system constraints. The single antenna greatly benefits the utility of the handset. At the base station, or ACN in this case, the transmitter is much stronger and space, power and cost are not the highest priorities making a two-antenna scheme more attractive.

A time division duplexing system uses the same frequency for the up and down links. This is a half duplex system, i.e., for a given time segment the uplink signal is transmitted from the handset and received at the ACN and in the next time segment the downlink signal is transmitted from the ACN and received by the handset. This system has the advantage that a simple transmit/receive (T/R) switch can be used in both the handset and at the ACN reducing the demands on the filters to reduce the leakage signal and making a single antenna possible. This is especially attractive if an antenna array is used on the ACN for more sophisticated antenna functionality. The disadvantage of this system is the increase in burst rate needed to transmit the same amount of information. For example, if the transmit/receive duty cycle is 50%, the burst rate (and peak transmitter power) must be increased by a factor of two over that of the full duplex system if the same information rate is to be maintained. This places higher demands on the link and the processing electronics.

B. Uplink Demodulation

1. General considerations

The recommended architecture requires a filter bank to demodulate the user signals which are in TDMA/FDMA format. Since user-to-user synchronized frequency hopping is employed, uplink processing can start by mixing the uplink signals with a synchronized hopping local oscillator to bring all of the uplink signals to a fixed IF which can then be followed by the bank of demodulators at appropriate carrier spacing. (The de-hopping can be performed with analog or sampled digital circuitry. The latter approach is feasible if the hopping bandwidth is only few 10's of MHz as in the Ultra Comm approach.)

Each demodulator in the bank must be able to synchronize rapidly to each uplink signal. For purposes of the discussion to follow it will be assumed that synchronization between the on-board demodulator and each uplink signal can be achieved to within a few microseconds through

a combination of GPS and ranging through the ACN. This degree of accuracy implies that the demodulator may have to acquire bit synchronization at the high rates of 32 to 64 kbps, but not at rates lower than about 32 kbps.

One approach to implement the bank is to use a dedicated demodulator for each uplink. There are chip-sets available for doing so and with a small number of uplink channels this is a reasonable approach. However, in order to implement a flexible bank in which the data rate per uplink can be traded-off against the number of uplinks, a more sophisticated approach is advantageous. The rest of this section presents a preliminary look at representative approaches using digital signal processing technology. (The uplink functions that follow the demodulator, e.g., decoding, collision resolution, address recognition, etc. are, of course, also of concern. However, from an implementation point-of-view the demodulator bank is probably the most challenging.)

2. Digital Signal Processing approaches

In order to provide a rough idea of the complexity required to implement a general purpose DSP-based demodulator bank some preliminary estimates of the rate of MACs (Multiply and Accumulate operations) have been made. The estimate is based on performing the basic demodulation function which is expected to dominate the total, but acknowledging that additional MACs will be needed for functions such as time synchronization, channel equalization, adjacent channel filtering, pulse shaping, gain normalization, etc.

The basic conclusion reached is that the demodulator bank can be implemented with a relatively small number (less than 10) of DSP chips.

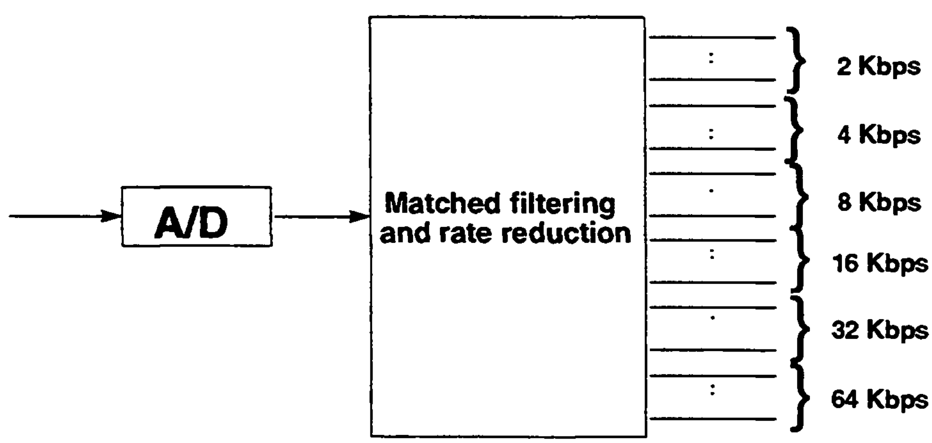


Figure VII-9 Basic approach to digital demodulation. The entire 4 MHz bandwidth is sampled at 8 MHz. Depending on the channel assignment, the A/D output stream is sent to a matched filter and downsampler resulting in the desired rate channel output.

Figure VII-9 illustrates the basic idea. The entire 4 MHz of bandwidth is sampled at the Nyquist rate (i.e., 8 MHz) and the 8 M samples per second (sps) stream is sent to the various channels that contain filters matched to the users' channels. (In practice a sampling rate higher than the Nyquist rate should be used to reduce the effects of aliased noise. A sharp analog

bandpass filter could precede the A/D converter that limits the aliased noise bandwidth and yet wouldn't cause significant distortion to the each user signal. Thus the sampling rate may not need to be too much higher than the Nyquist rate.) For one of the 64 KHz channels, the 8 Msps output stream of the A/D converter is passed through a digital matched filter of length 8M/64K ~ 128 samples. The output of the matched filter is then downsampled at the channel rate (i.e., 1/64,000 sec.). The rate of MACs for this channel is equal to 128 x 64,000 = 8M MACs per second. Since the number of samples required per symbol varies inversely with the symbol rate, the number of MACs per second is independent of the channel rate. A systemization of this straightforward approach is equivalent to the *polyphase* implementation [Proakis & Manolakis, Chapter 10]

Although the computational complexity of the demodulator seems quite high it is still likely that the hardware implementation of the design can be carried out with a small number of DSP chips such as the Texas Instruments (TI) C6201. Envisioned for use in cellular base stations, the C6201 will likely be the processor of choice in next generation digital cellular and PCS systems. The C6201 is capable of executing 1600 million instructions per second (MIPS). This feat is accomplished with the use of 8 parallel arithmetical logic units (ALUs), each capable of running 200 MIPS. However, closer examination of the ALUs reveals that only two are capable of multiplies and two more are capable of adds. Therefore, the C6201 is capable of 400 million MACs per second.

Since it takes on the order of 8 M MACs per second per channel it is seen that a single DSP chip should be capable of demodulating about 50 user channels. To be conservative, perhaps the MAC rate should be doubled which would still yield over 20 channels per DSP chip.. (Recent studies on the use of DSPs in radio communications systems [Kostic & Seetharaman] suggest that this should be sufficient "margin".)

If it is necessary to implement a large number (more than about 200) of low rate channels an alternate approach to processing the users' signals can be derived by exploiting the slower signaling rate of the users on the 16 KHz, 8 KHz, 4 KHz and 2 KHz channels By exploiting the bit-synchronous nature of the lower rate channels, it becomes possible to use an FFT for the channelization. Symbol detection would logically be carried out in the frequency domain. Figure VII-10 illustrates the concept. The advantages of this approach will become evident when the computational complexity of the two schemes are examined.

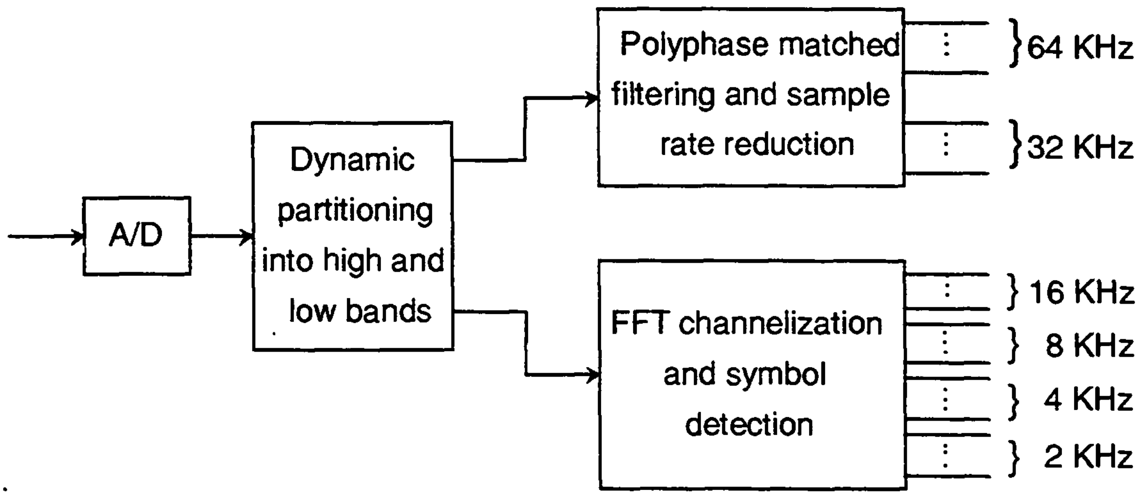


Figure VII-10 A hybrid approach to demodulation. By splitting the 2 MHz band into "high" (i.e., 64 and 32 KHz channels) and "low" (i.e., 16 KHz, 8 KHz, 4 KHz and 2 KHz channels) segments and processing each separately, considerable complexity savings can be achieved. The gain comes from the fact that the low band users can be safely assumed to be bit-synchronous, allowing for channelization with an FFT.

Significant savings in computational complexity for the lower rate channels can be achieved with the FFT approach whereby the 4 MHz system bandwidth is partitioned into two parts, the high bandwidth users and the low bandwidth users, and each group is processed separately. Assuming that 2 MHz has been allocated to users of the 64 and 32 KHz channels and 2 MHz to the 16 KHz and below channels, and further assuming that each 2 MHz band is effectively sampled at the Nyquist rate (i.e., 4 Msps) one can easily see that a 2048 point FFT would be required to resolve the smallest (i.e., 2 KHz) channels in the lower band. Moreover, for the case where only 2 KHz channels were in use, the FFT would only need to be computed every 1/2K = 500 microseconds. These computational requirements are easily within the capabilities of the C6201, which can compute a 2048 point FFT in 45,654 cycles or 228 microseconds. Even in a "worst case scenario" where the entire 4 MHz is allocated to the lower band, a 4096 point FFT would be required to resolve the 2 KHz channels. The C6201 computes a 4096 point FFT in 62,669 cycles or 314 microseconds, more than adequate speed for a 2 KHz channel. (The C6201 relies on the radix-2 and radix-4 algorithms to compute FFTs whose lengths are powers of 2 and 4, respectively. Consequently, FFT whose lengths are powers of 4 can be computed more efficiently since the radix 4 algorithm requires fewer multiplies than the radix-2.) On the other hand, for the case where only 16 KHz channels were present in the lower band, a 256 point FFT is sufficient for resolving the channels. However, given the higher rate at which these users are transmitting, the FFT would need to be performed every 1/16K = 62.5 microseconds. This is still easily achievable with a C6201, which can perform a 256 point FFT in 13.8 microseconds. Ideally, it is desirable to perform the longest FFT (i.e. 2048, assuming that 2 MHz is allocated to the lower band) at the fastest rate (i.e., 62.5 microseconds). Unfortunately, this is beyond the capability of a single C6201 since a 2048 point FFT requires 228 microseconds. Note also that the FFT merely performs the "channelization" and that further processing (e.g., matched filtering) is still necessary for the symbol detection, implying that two C6201s would probably be necessary to fully process the lower band anyway. Nonetheless,

using 2 C6201 chips to process the lower band represents a significant savings in complexity since it is the lower rate channels that are most demanding with the polyphase scheme. Note that the upper band (i.e., the 64 and 32 KHz channels) can be processed with the polyphase scheme using one or two C6201s. So, the hybrid approach of polyphase matched filtering in the upper band and FFT channelization followed by transform domain detection for the lower band has requires about 4 C6201s (or 8 with a safety factor of 3) in a worst case scenario.

C. Handheld Units

The ultimate physical realization of the wireless handheld unit should be compatible with both computer and human, e.g., voice, interfaces. This could take several forms including:

- a PC card (or cards) which can be inserted into other equipment
- a cellular-style handset with a computer interface port
- a small computer-style unit with display, input device and additional interfaces, similar to Apple Newton (R.I.P) or Palm Pilot
- a self contained unit that includes the wireless subsystems, voice processing, and computational facility with peripheral interfaces (this is the HMT approach as described in the GOTS section)

Whichever form is selected there are minimal functions that must be included, and these are:

- all RF uplink and downlink data, signaling, security and control functions (in essence, all the ACN/HH wireless subnet functions)
- user to ACN/HH network interfaces
- TRANSEC

Given the state of existing commercial realizations (cellular, PCS, and ISM band equipment) and technology under development by industry and DoD there is little doubt that the handheld unit can be realized in the equivalent one (or perhaps two) PC cards, even including GPS and Fortezza (and possibly stronger) security. However, in order to achieve this, some ASIC development and careful attention to packaging will be necessary. For initial demonstration implementations, other techniques would yield adequate performance in larger sizes with less development cost.

Because of the intense interest in handheld wireless communication in a number of DoD organizations there is motivation to consider the cooperative development of the physical hardware. This is largely a programmatic decision that would need to be made.

VIII. Applicability of Cellular, PCS and other COTS Technologies

Throughout this report attention has been drawn to applicable COTS technologies, be they hardware, software protocols, standards or system approaches. It is felt that the COTS world has much that can be offered, but does not provide a direct "plug and play" solution to providing ACN handheld services. In this section we summarize the applicability (or shortfalls of COTS technology) in support of this conclusion. We are not trying to summarize all features of these systems. More details can be found in [Goodman], [Gibson], and [CECOM TPCS]. The reader should also refer to Section IV-G which includes a discussion of recommended system architecture and its relationship to COTS technologies.

(Note: This section is not addressing the issue of whether or not commercial infrastructure should be used when it is available in a theater of operation. That is an operational and policy issue beyond the scope of this study. However, if this mode of operation is desired, it would affect the design specifications of protocols and handsets which would then need to be multi-mode.)

A. Cellular (850 MHz) and PCS (1.9 GHz) Systems

The reality of cellular and PCS systems that are so ubiquitously deployed leads to the question: "Why not fly a cellular or PCS base station?" (Or, at least why not use a terrestrial base station with the ACN acting as a transponder?) There are some general observations of applicability and shortfalls that will be made before discussing specific systems.

1. General applicability

- connection-oriented service (for voice, streaming data, and PPP-type data protocols) is inherent
- connectivity to the terrestrial switched infrastructure using commercial standards plant is inherent
- protocols for connection-oriented service provision are standardized and non-proprietary
- handover procedures are inherent
- handset technology is impressively mature and lightweight (although an investment would need to be made to convert operating frequency)
- OEM chip sets are available commercially for most systems
- most of the systems include signal processing which mitigates terrestrial multipath at close range
- the digital systems include integrated paging and short messaging
- base station technology is available, although not in flyable form
- some of the specific approaches provide reasonable spectral efficiency (bps per Hz) under controlled circumstances
- some signal structures for use on the ACN uplink may be applicable

2. General shortfalls

- all of the systems are easily jammed or disrupted by a hostile party using a terminal similar to a handset that is nearly undetectable
- there are no existing self-contained flyable base stations; significant development would be required
- base stations generally rely on the PSTN switched plant for user-user connections; only one realization of a terrestrial stand-alone, deployable base station has been identified
- specific base station and handset realizations may be proprietary
- connectivity maintenance procedures and handover are designed for static terrestrial plant, not a dynamic backbone as in a network of airborne platforms
- protocol and signal formatting, e.g., TDMA frame structures, are designed for short ranges (a few miles); operating ranges of 100-200 miles to ACN will require changes which may be non-trivial and expensive (A recent TTCP TP6 Workshop on UAV-based Cellular Radio reported on some of the specific difficulties with timing and Doppler .)
- data rates are not adaptable to channel conditions
- some systems may not be able to compensate for Doppler shifts associated with an airborne platform or a long range multipath environment
- support for efficient and responsive bursty data transmission is not currently available, with the exception of CDPD (which is a symmetric data rate protocol) and an emerging CDMA packet overlay (IS-707)
- asymmetric data rate services are not available
- there is no provision for traffic or user precedence or priority
- none of the systems can be considered LPD

3. AMPS and CDPD

The AMPS system is a narrowband symmetric analog system and is not a serious contender for ACN application.

However, aspects of the CDPD (Cellular Digital Packet Data) overlay, whereby individual 30 KHz AMPS frequency channels are used for packet data transmission at a rate of at most 12.5 kbps (after error control coding) may have applicability. The specific narrowband physical layer used in CDPD is not desirable, Also, the physical data rate of CDPD is fixed and hence would not adapt to widely varying channel conditions. However, the protocols for user registration, handover and multiple access, and error handling should be examined. Also, the signal processing used in multipath mitigation may be worthwhile to consider.

The ability of CDPD to operate at high spectral density, i.e., with closely packed frequencies, was not determined. In a cellular environment adjacent frequencies are generally assigned to different cells. Using every other frequency channel the spectral density would be 12.5 kbps per 2x30 KHz or about 0.2 bps/Hz if careful power control and filtering were used.

CDPD may offer an approach to some aspects of ACN uplink multiple access. However, it has been noted in Section III that performance could be improved with a multi-channel extension of the basic CDPD access protocols.

4. IS-136 (formerly IS-54) TDMA AMPS overlay

IS-136 is another overlay on the AMPS system whereby individual 30 KHz AMPS frequency channels can be converted in format to digital TDMA, thereby increasing capacity from one to 3 or 6 voice circuits per frequency. It is circuit-oriented. Each IS-136 frequency channel operates at a burst data rate of 24.3 kbps (after rate 1/2 coding) comparable and with a frame time of 40 msec.

As with CDPD, the specific narrowband physical layer used in IS-136 is not desirable. The physical data rate of IS-136 is fixed and hence would not adapt to widely varying channel conditions. However, the protocols for user registration, handover and multiple access, and error handling should be examined. Also, the signal processing used in multipath mitigation may be worthwhile to consider.

The ability of IS-136 to operate at high spectral density, i.e., with closely packed frequencies, was not determined. In a cellular environment adjacent frequencies are generally assigned to different cells. Using every other frequency channel the spectral density would be 24.3 kbps per 2x30 kHz or about 0.4 bps/Hz if careful power control and filtering were used.

In summary, the IS-136 signal structure may well serve as a model for the ACN uplink, although a packet access technique would need to be added.

5. GSM

GSM (Global System for Mobility) was designed for digital cellular applications from the start and is not an overlay on an analog system. It is used at both cellular frequencies (outside the US) and PCS frequencies (globally). It is voice circuit oriented

GSM employs FDMA/TDMA (with an eight slot 4.62 msec frame at a burst rate of approximately 135 kbps including rate 1/2 coding). The uplink can use user-user synchronized frequency hopping (at a rate of about 217 hops/second) over 25 MHz and thus could provide at least some of the benefits of (non-secure) spread spectrum. A packet system, GPRS (General Packet Radio Service), is probably going to be added, but not of the asymmetric type.) The GSM signal structure may well serve as a model for the ACN uplink. Although GSM terminals are designed as time-duplexed symmetric units, the downlink might be utilized to operate at a total rate of 135 kbps, thus providing some degree of asymmetry.

The ability of GSM to operate at high spectral density, i.e., with closely packed frequencies, was not determined, although its frequency hopping gives it somewhat of an advantage in that a users won't be "stuck" with interference from a high power user at an adjacent frequency. In a cellular environment adjacent frequencies are generally assigned to

different cells. Using every other frequency channel the spectral density would be 135 kbps per 2x200 kHz or about 0.34 bps/Hz if careful power control and filtering were used.

The TDMA frame structure and duplexing technique is designed for a maximum range of 36 km from user to base station. System changes would be needed to accommodate the longer range to the ACN.

6. IS-95 CDMA

The IS-95 CDMA (Code Division Multiple Access) digital cellular standard is notable for its use of direct sequence spread spectrum for creating multiple channels, combating multipath, and enabling novel handover algorithms. Its spread spectrum bandwidth is 1.25 MHz, relatively narrow, because it was designed to be equivalent to 10% of the AMPS uplink or downlink block of frequencies in order to permit operators to transition. It is voice circuit oriented. On its uplink the user spread spectrum signals are not synchronized sufficiently to remain orthogonal and hence each user acts as white noise to each of the others. (A similar signaling technique will be used with the Globalstar MSS.)

Evaluating the capacity of IS-95 (or equivalently its spectral efficiency) under realistic conditions has been controversial. However, it can be said with confidence from basic principles that the spectral efficiency (bps per Hz) of a single cell in a multiple access environment will be limited by mutual interference to $(Eb/No)^{-1}$ where Eb/No is the energy-per-bit to noise density ratio required by the underlying modulation and coding scheme. At best Eb/No will be 5 dB (and more likely around 8dB under fading conditions) and hence the spectral efficiency will be between somewhere between 0.16 to 0.32 bps/Hz under perfectly power balanced conditions. Non-ideal power balancing is usually taken to penalize IS-95 systems by 2 dB and hence the efficiency is perhaps 0.1 to 0.16 bps/Hz. This translates directly into relatively low capacity compared to the other cellular PCS schemes. (It should be added, however, that IS-95 was designed to work in a cellular environment with complete frequency reuse from sector to sector and cell to cell. In this case IS-95 can be quite competitive with the other schemes that generally can not be so intense in frequency reuse.)

It is felt that unless a relatively dense population of ACNs are in-theater, the ACN environment is closer in nature to a single cell. Consequently is not felt that IS-95 physical later technology should be recommended for the ACN application because of its relatively low potential capacity. However, its protocols and handover strategy should be considered. Changes would need to be made to accommodate the longer range from users to the ACN than to a terrestrial base station.

Additionally, it should be noted that the only deployable self-contained base station that we became aware of was an IS-95 unit supplied by Qualcomm that could handle about 20 voice channels. Its power and weight (2 kW, 650 lbs) were not suitable for flight., and changes in signaling to accommodate ACN ranges are likely to be significant. In addition, Qualcomm very recently introduced a small 75 lb base station transceiver (BST) which provides the front-end for an IS-95 cell. It apparently requires connection to an external switch in order to achieve user-user connectivity; however, this unit was not researched in detail.

7. Emerging Commercial Developments

The commercial wireless industry is currently considering a new wave of developments which generally involve one or more of: higher data rates, wider band spread spectrum, data-oriented services, e.g., IS-707 packet service for CDMA, and novel platforms. It is too early to tell which of these developments will lead to standards upon which ACN handheld technology could or should be based. However the community should at least be aware of IMT-2000, ETSI, and Wideband CDMA, even though they are all primarily circuit-oriented systems.

Recent articles provide a readable summary of the current foment in the commercial wireless industry over the choice of new directions to take. [EETimes, December 8, 1997, "The World Phone- Designers Puzzle Over New Network Connections and Communications Week International, December 16, 1997, "Wireless Phone Standards Spark Controversy"]

B. Mobile Subscriber Satellite (MSS) Systems

The deployment over the next few years of several commercial Mobile Subscriber Satellite (MSS) Systems, e.g., Iridium, ICO-P, Globalstar, and Orbcomm, (see [McIntosh] for a more complete listing) raises the question of whether any of their specific technologies, if proven successful, are applicable to the ACN. This study was not able to go into the depth required to evaluate each of these systems, but we can list their generic applicability and shortfalls as in the next subsections.

The overall recommendation at this point, however, is that none of the MSS systems appear to have the characteristics of the recommended architecture. They are all symmetric voice circuit-oriented systems that would not work well in a data-intensive secure military environment. In addition, the systems are designed to proprietary specifications. However, specific technological features, e.g., antenna arrays, transceivers, handover protocols, and on board processing (in the case of Iridium) may indeed be applicable. It is recommended that a closer look at be taken at some of the selected features. However, optimism regarding technology transfer to the government may not be called for due to the highly competitive nature of the business.

1. General applicability

- connection-oriented service (for voice, streaming data, and PPP-type data protocols) is inherent
- connectivity to the terrestrial switched infrastructure using commercial standards plant is inherent
- handover procedures are inherent
- handset technology should be available (although an investment would need to be made to convert operating frequency)
- systems include signal processing which mitigates terrestrial multipath at fairly long range
- systems are expected to include integrated paging and short messaging
- systems are designed for reasonably high spectral efficiency (bps per Hz)

- low altitude systems are designed to operate with significant Doppler shifts
- signal structures for use on the ACN uplink may be applicable
- some systems include a variety of data rates adaptable to channel conditions
- some systems include the ability to service a user with more than one spacecraft, hence providing some diversity from terrestrial blockage

2. General shortfalls

- all of the systems are easily jammed or disrupted by a hostile party using a terminal similar to a handset that is nearly undetectable
- there are no existing ACN-flyable base stations; significant development would be required
- base station and handset realizations are proprietary
- protocol and signal formatting, e.g., TDMA frame structures, are designed for satellite ranges; operating with ACN might require changes which may be non-trivial and expensive
- some systems may not be able to compensate for Doppler shifts associated with an airborne platform or a long range multipath environment
- support for efficient and responsive bursty data transmission does not appear to be available (although it might be under development in some systems)
- asymmetric data rate services are not available
- there is no provision for traffic or user precedence or priority
- none of the systems can be considered LPD

C. Small User Data Satcom Systems

There is another generation of commercial satellite systems in the development phase that will be deployed in the next century more oriented to providing data services to small ground terminals. These systems include Motorola Celestri, Hughes Spaceway, Teledesic, and others. However, none of these systems are intended to provide services to mobile handheld users. They all operate in the microwave band (typically around 30 GHz uplink and 20 GHz downlink) and require ground terminal antennas with apertures from one to several feet (resulting in narrow beamwidths). The physical characteristics of these systems would not be applicable to the ACN handheld system.

Further investigation may be warranted to see if any of their technologies, e.g., protocols, are applicable. But as with the MSS systems, optimism regarding technology transfer to the government is not warranted due to the highly competitive nature of the business.

D. Paging

Paging in the commercial world is done either with a dedicated paging system or, more recently, as messages transmitted via cellular or PCS systems. Similarly, the ACN paging system could be designed based on the commercial open paging standards or integrated with the high rate downlink. Either solution is viable.

There is precedent for adapting the commercial dedicated paging system to DoD use. In particular, a recent joint project undertaken by Army CECOM and Lincoln Laboratory demonstrated a secure anti-jam paging capability via Milstar [Shake]. The uplink is at EHF and uses the highly jam resistant Milstar waveform; the satellite receives and processes the uplink, then converts it to the UHF downlink. It is notable that a contractor, Motorola, was able to modify its commercial paging receiver to operate in the military UHF band.

E. ISM Band Communication Equipment

Communication equipment that operates in the ISM bands (915 MHz, 2.4 GHz, 5.7 GHz) has been an active area of commercial development. This activity has been spurred by the fact that as long as the equipment is FCC type certified, a license to operate is not required by the user. The FCC rules for this equipment type (usually referred to simply as Part 15) specify that it must operate as spread spectrum (either frequency hopping or direct sequence). Equipment that is available ranges from chips, to OEM boards, to PC Cards, to small battery operated units, to drawers requiring wall-plug power. Of potential relevance to the ACN are modems and wireless LANs. The generic applicability and shortfalls are given below followed by recommendations.

General applicability

- spread spectrum is used (to 80 MHz)
- the two lower operating frequencies are within the range of interest to the ACN
- a variety of rates and data transmission services are available
- the form factor for a many of the available equipment is small and can be battery operated
- at least some standardization is taking place. e.g., 802.11 wireless LAN

General shortfalls

- all would require a change in operating frequency and spread spectrum bandwidth
- all of the systems are easily jammed or disrupted by a hostile party using a terminal similar to a handset that is nearly undetectable
- specific protocols and waveforms may be proprietary
- protocol and signal formatting, e.g., TDMA frame structures, are designed for short ranges (usually a few hundred feet); operating ranges of 100-200 miles to ACN may require significant changes
- some systems may not be able to compensate for Doppler shifts associated with an airborne platform or a long-range multipath environment
- asymmetric data rates services are generally not implemented
- wireless LAN equipment generally operates at high data rate (1-2 Mbps) in both directions
- none of the systems can be considered LPD

Recommendation

While the hardware that is available is not directly applicable to an operational ACN, COTS modem equipment could be considered for:

- early experiments, demonstrations and exercises; this is particularly true of the modem units which could possibly serve as downlinks
- serving as a base for future modification to DoD needs, e.g., change in operating frequency or use of secure spreading sequences

It is unlikely that the wireless LAN equipment can be utilized in the ACN application without substantial modification, i.e., essentially requiring a new design.
[NRaD] reached similar conclusions.

F. Emerging COTS Concepts

The commercial world is generating new wireless communication concepts at a dizzying rate. Some of these concepts share at least some attributes with the ACN/HH. Of course none are intended to provide the security, priority structure, jamming protection and other military features that ACN/HH requires. However some of the technology components, e.g., phased array antennas, are worth investigating.

A short list of some of these emerging technologies are found in the following systems:

- digital audio broadcasting standards, e.g., ETSI' 300 operating at over 1 Mbps, which could provide a starting point for a design of the downlink waveform
- packet services that may be provided over MSS satellite systems
- IMT-2000, the European next generation cellular system with data service
- Angel Technologies proposed High Altitude Long Operation manned relay for Internet traffic
- TransSky's proposed terrestrial-based moderate rate Wideband CDMA for Internet traffic
- GEC Marconi' Hazeltine's Skysat aerostat system for cellular communication
- ALOHA Network's development of a wirelesses LAN approach using CDMA waveforms (non-orhtogonal) combined with ALOHA access for multiple access with bursty data

IX. Applicability of GOTS Technologies

There are a number of government off the shelf (or in active development) technologies that have potential relevance to the ACN handheld system. This section summarizes findings on several.

A. GloMo

The DARPA/ITO GloMo (Global Mobile Communication) program has funded a number of technology developments spanning essentially 5 areas. The general goal is to "advance the state of the art in mobile, wireless, multimedia information systems technologies". The developed components were not a-priori required to be coordinated for insertion into a particular integrated system, although we should note the GloMo community has a number of Integrated Capability Tracks which are intended to tie together a number of subsystems developed separately. These ICTs are not intended to produce an off-the-shelf system. However, these efforts when analyzed should provide lessons learned on how to design an integrated system retaining the algorithms but not the specific implementations.

It should be noted that GloMo has concentrated more on distributed peer-peer networking ("packet radio") rather than the base station-centric architecture that is more natural for the ACN. Hence, it should be expected that certain aspects of GloMo may well fit in with ACN, but that it does not provide the total ACN solution. The comparison between peer-peer and base station-centric networking was discussed in [NRC].

1. Design infrastructure

This is a set of efforts concerned with tool developments which will support simulation and synthesis of wireless systems from IC components design to network protocol design to corresponding simulations complementing the designs. This is an area that is relevant to the design and simulation of the ACN/HH network. UCLA's Maisie design and simulation environment is applicable. A design based on the Advanced Communications Engine (ACE) - (Hughes) might be appropriate depending on the particular radio API. The design techniques at Cadence Berkeley Labs on Logic Synthesis of Low Power Applications is another key design tool. There are a number of other relevant design tools as well. These design support environments will make the design and simulation of ACN/HH specific components and subsystems simpler.

2. Untethered nodes

This is a very ambitious effort which lays the groundwork for a new generation of software radios. A "universal radio port" and "universal radio bus" is being developed. The latter interconnects the antenna, digital radio, environment module, the baseband signal processor, networking support and power source "modules". One may have the impression that one can pick alternative COTS/GOTS realizations for any of these modules and thereby construct a suitable system, but this is may not be realistic.

A more workable solution is to clearly define a full logical interface between each interface and physical interfaces where appropriate. Within each module, one wants to define a functional specification, performance parameters and candidate algorithms to realize important parts of the functionality. Towards this end a "Radio API" has been developed and published which may prove to be applicable.

In accord with the preceding discussion, we feel that there is little, if any, specific hardware or software code that can be carried over from GloMo for the ACN/HH radio proper. However, the algorithms and interface specifications may well be a valuable carry over.

3. Wireless networks

This is an area where both the work in GloMo in network algorithm design in the areas of mobility and mobile multicast and security will be valuable. This work complements and will can impact the international standards activities going on in the IETF. A small amount of the actual code may be ported to particular subsystems (for example those subsystems built on a Unix derivative such as Linux), whereas the bulk of the code may have to be completely rewritten. Some of this code will be based on GloMo developed algorithms but much more will be completely new code and will require new algorithms simply because the ACN/HH has a number of new radio environments.

4. End-to-end networking and security

Any work that GloMo accomplishes in building gateways to the commercial infrastructure would be applicable. The major twist would be to limit access for security and information warfare reasons. The military security needs are necessarily more severe than the commercial ones and this adaptation is not easy as witnessed by the slow development of DMS and MISSI among others.

There are some GloMo projects that specifically address security services in the mobile networking environment, including various authentication and identification algorithms. A "red team" approach is also being used. Particular attention is being paid to applications of Fortezza. This is an area that could be of direct relevance to ACN/HH.

5. Mobile applications support

This is an area that can greatly benefit the utility of the ACN/HH. The relevant work going on in GloMo is running applications in a severely bandwidth-limited environment (as in the ACN/HH) where it is extremely difficult to guarantee a desired Quality of Service parameter (adverse, unpredictable propagation conditions is the limiting factor). The GloMo work in intelligent caching and various proxy agents which ease distributed application execution is both excellent and directly relevant.

B. Handheld Multimedia Terminal (HMT)

The Handheld Multimedia Terminal (HMT) is being developed by a team (ITT, Honeywell, Sarnoff, and MCS) and is funded as a TRP and a GloMo project. Because it is expected to implement a capable handheld unit at data rates of interest it is worthy of consideration as discussed below. Preliminary units are expected to be demonstrated in mid 1998.

The HMT implements a peer-peer wireless multi-hop local area network. Its data rates go from 125 kbps to 1 Mbps (minus overhead) per transmission link. Anticipated link ranges are a few kilometers (depending on conditions). It operates in the 2400-2480 MHz ISM band employing direct sequence band spreading at a chip rate of 16 Mcps (on each of offset I&Q streams). The band is divided into four equal frequency segments, one of which is used for control. In its unicast mode each data transmission consists of an RTS/CTS exchange between nodes followed by data transmission and an ACK. During the RTS/CTS exchange the two units also negotiate data rate, power level and band segment. Each RTS or CTS takes 184 microseconds. Multicasting and broadcasting modes are also included. Data packets can be relayed through up to 3 nodes in order to reach their intended destination. The system autonomously organizes its routing tables with a distributed algorithm; there is no central controller. A prioritized queueing scheme is used to give higher priority to streaming services such as voice. Consideration will be given to implementing a cluster-head routing concept similar to the NTDR in the future. The HMT units are half-duplex. The modem includes a 4 finger RAKE adaptive receiver. The bulk of the demodulator processing will be done in an FPGA. Eventually the modem will be implemented with an ASIC. The unit will include multimedia applications software, especially for image processing.

A Fortezza card will be included for COMSEC. DES encryption is also included for commercial applications. An FPGA-implemented KGV-10 will provide TRANSEC direct sequence spread sequences (although initially the Barker and Gold synchronization code sequences will be uncovered).

Applicability of HMT to the ACN/HH

Downlink

The HMT modulator-demodulator (modem) can be considered as a way to implement a high rate downlink using its broadcast/multicast modes. The spread-spectrum modem, if proven in trials, may be quite efficient in its use of power (low required Eb/No).

Multiple 1 Mbps broadcast/multicast streams can be created using multiple HMT transmitters boosted by high power amplifiers. Advantage can be taken of its CDMA/FDMA structure by, for example, assigning different aircraft or antenna beams to different band segments. However, the fact that there are only 99 link-layer address and that each unit can respond to only 4 of them could limit multicasting flexibility and efficiency. Additionally, it would remain advantageous to feed the downlink with packet streams scheduled by the ACN/HH which merge multiple simultaneous uplinks.

Uplink

The HMT is not designed to be a "many-to-one" system as is required for the recommended ACN/HH uplink. In particular, HMTs transmitting in the same segment of the band create mutual CDMA interfere with each other and limit spectral efficiency to at best about 0.1 bps/Hz (determined by the modulation/coding efficiency and accuracy of power control). The chip sequences used for bandspreading are not synchronized among users with an accuracy that would keep them orthogonal. Other spread-spectrum multiple access structures, e.g., coordinated frequency hopping or synchronized direct-sequence (difficult) should achieve spectral efficiencies closer to 0.5 bps/Hz. The lowest data rate provided is 125 kbps, making it difficult to close the link at the desired long ranges, particularly with their transmitter limited to a peak of 1 watt. Lower data rates and/or transmitters that can trade peak and average power will be needed.

Other issues

a) The implementation is not flexible with regard to frequency band or RF bandwidth. This flexibility is highly desirable to have when considering the difficulty of clearing worldwide allocations.

b) Because HMTs are RF half-duplex and do not use a system-wide frame structure, a significant redesign of protocols, timing, or hardware (or all three) would be required in order to accommodate an ACN many-to-one and one-to-many architecture.

c) Some aspects of the implementation are proprietary in accordance with TRP agreements.

C. MEMS

The DARPA/ESO MEMS program (MicroElectroMechanical Systems) is developing a number of miniaturized components with potential direct relevance. These include RF power amplifiers, filters, receivers and signal processors. These technologies will ultimately help solve the ACN/HH packaging problem, but are not required to implement a (heavier) near-term demonstration system.

D. Ultra Comm

Ultra Comm is a DARPA project being performed by a Raytheon-E-Systems led team which will bring together a number of technologies, including MEMS, in order to realize a flexible, and capable RF receiver module in a PC Card format. If successful, this technology can be considered a building block for an ACN/HH receiver (and possibly demodulator) that can be used in the handheld unit or in the ACN base station.

E. Software Reprogrammable Radios

DoD is moving towards specifying that future radios will be required to be modular and software reconfigurable. Towards that end, the PMCS (Programmable, Modular Communication System) program has been established. Accordingly, the ACN/HH implementation should strive to conform to this architecture and take advantage of specific technology developments as appropriate. Commercial industry has been considering and debating this architecture as well.

The SPEAKEASY and JCIT programs have already developed radios that are forerunners of this architecture. However, their form factors (rack mounted) do not lend themselves to direct ACN/HH application.

F. SUO

The DARPA/TTO SUO [SUO] program is developing communication and geolocation technologies for Small Unit Operations requiring small, i.e., handheld radios. SUO incorporates both peer-peer and reachback communication connectivity. Because each program can provide technology solutions for the other, it is advantageous that SUO and ACN/HH work interactively.

G. CONDOR

Condor is "An NSA program to develop and demonstrate secure voice and secure net broadcast services over commercial cellular infrastructure" and permits interoperability with STU-3 secure phone equipment. [www.nsa.gov/programs/missi/condor.html]. This technology is likely to be applicable to the ACN/HH and should be closely tracked.

H. Soldier Phone

The Soldier Phone is a Rockwell, BEL project based on the "Wirecom Engine" TRP. The ACN Handheld team was not briefed on this system, but understands its main characteristics to be:

- peer-to-peer wireless data system
- lightweight radio
- anti-jam features
- data rates up to 2 Mbps

From the description available it is believed that the soldier phone will have a similar limited direct applicability to the ACN/HH, but may also have technological components or subsystems that should be carefully examined.

I. Other Systems

The ACN Handheld study team heard numerous briefings on other GOTS systems. While several have features that may be usable by the ACN/HH or may require interoperability there does not appear to be specific technology that may be directly applied. A listing of these additional briefings follows:

- SDR (Surrogate Digital Radio)
- NTDR (Near Term Digital Radio)
- Handheld SINCGARS
- RAP (Radio Access Point)
- Army Wireless LAN
- Tactical Internet

X. Summary of Conclusions and Recommendations

The major conclusions and recommendations can be summarized as follows.

- A multi-Mbps multimedia handheld communication service using the ACN is feasible
- ACN handheld services should make use of mobile networking concepts such as those explored in the Warfighter's Internet study
- An asymmetric architecture (lower rate uplink than downlink) is recommended
- Adaptive, flexible physical links integrated with upper level protocols and applications are desirable
- There are numerous GOTS and COTS (or in development) subsystem, component and protocol technologies that are applicable
- No COTS or GOTS system has been identified as a complete "plug and play" solution to providing secure, flexible, efficient and scalable ACN interactive handheld services
  - COTS does not meet minimal AJ and LPD requirements
  - Cellular, PCS and MSS systems are limited by their symmetric circuit-switched architecture (although data services are evolving)
  - Wireless LANs do not provide asymmetric services with low rate uplinks
  - The commercial market should continue to be tracked
- Useful near-term demonstrations of the ACN/HH concepts can be achieved with off-the-shelf components, but will not have the capacity, efficiency, range, security and form-factor of a final system
- A flexible approach to the selection of operating frequency and bandwidth is necessary
- Development is required in the areas of
  - detailed system design
  - integration with mobile networking concepts such as those in the Warfighter's Internet study
  - detailed physical layer designs and protocols
  - efficient uplink multi-channel multiple access techniques
  - realization of on-board processor
  - adaptive robust physical links
  - ACN antenna concepts: shaping, sectoring, nulling
  - low power handset components
  - interfacing with legacy radio networks

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13. ABSTRACT (*Maximum 200 words*)

This report examines handheld wireless communication services for the tactical theater that can be provided by a high altitude airborne communication node (ACN) such as the Global Hawk unmanned air vehicle (UAV). An integrated system approach supporting four categories of service is described. The four handheld services included are: a circuit-oriented service for voice and other streaming traffic, a data-oriented service for packets, a tactical broadcast service, and a paging service. Technical issues addressed include: frequency band selection, electromagnetic compatibility, link performance, antenna designs, multiple access, implementation, and security. A system architecture which is asymmetric with regard to its uplink and downlink and which incorporates on-board processing is recommended. The applicability of commercial and government off-the-shelf technologies (COTS and GOTS) is investigated. No single off-the-shelf system was found to satisfy all desired characteristics.

14. SUBJECT TERMS

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